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CONTRIBUTIONS TO REMOTE SENSING OF SHALLOW WATER DEPTH WITH THE WORLDVIEW-2 YELLOW BAND

by

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Remote sensing of the bathymetry in shallow water of Tampa Bay is examined using the multi-spectral imagery from the Worldview-2 satellite. Utilizing the newly available yellow spectral band in a ratio algorithm, five ratio combinations are compared against a digital elevation model of Tampa Bay. Following the work of Stumpf et al. (2003) ratio algorithm and starting with the work of Loomis (2009) and Densham (2005), the yellow band was combined with the blue, green and red bands separately. These three ratio combination results were compared with the results of the more traditional blue/green combination and a green/red combination. Three transects lines were drawn in a shallow reef area in the north portion Tampa Bay, Florida on Mullet Key near Fort de Soto State Park. In water under 2 meters depth, the substrate contributions were significant in all ratio derived bathymetries. The addition of the yellow band provided more information about the bathymetry than the previous blue/green and green/red combinations by adding more combinations that utilized a reflectance level difference. The yellow band demonstrates less sensitivity to bottom type in two of the transect lines.

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CONTRIBUTIONS TO REMOTE SENSING OF SHALLOW WATER DEPTH WITH THE WORLDVIEW-2 YELLOW BAND

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ABSTRACT

Remote sensing of the bathymetry in shallow water of Tampa Bay is examined using the multi-spectral imagery from the Worldview-2 satellite. Utilizing the newly available yellow spectral band in a ratio algorithm, five ratio combinations are compared against a digital elevation model of Tampa Bay. Following the work of Stumpf et al. (2003) ratio algorithm and starting with the work of Loomis (2009) and Densham (2005), the yellow band was combined with the blue, green and red bands separately. These three ratio combination results were compared with the results of the more traditional blue/green combination and a green/red combination. Three transects lines were drawn in a shallow reef area in the north portion Tampa Bay, Florida on Mullet Key near Fort de Soto State Park. In water under 2 meters depth, the substrate contributions were significant in all ratio derived bathymetries. The addition of the yellow band provided more information about the bathymetry than the previous blue/green and green/red combinations by adding more combinations that utilized a reflectance level difference. The yellow band demonstrates less sensitivity to bottom type in two of the transect lines.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

DEM	Digital Elevation Model
ENVI	Imagery processing software from ITT Visual Information Systems
GRS80	Geodetic Reference System 1980
IMD	Image metadata file
IR	Infrared wavelength
NAD83	North American Datum 1983
NIR	Near infrared wavelength
NOAA	National Oceanic and Atmospheric Administration
RGB	Red green and blue bands
ROI	Region of interest
TOA	Top of the atmosphere
USGS	United States Geological Survey
WV-02	Worldview-2 Satellite
YGB	Yellow, green and blue bands

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I. INTRODUCTION

The advent of multispectral satellite imagery in the last few decades has allowed the scientific community new opportunities of research into remote sensing of the physical world. In the field of ocean color, there have been several applications of multispectral imagery that have become useful to the scientific and naval community. Increased commercial satellite data has expanded the breadth and scope of areas under research that include coastal bathymetry. Customary methods of surveying the ocean, using airborne, or sea based platforms, are time intensive and costly

Finding a way to rapidly determine accurate usable bathymetry with little logistical cost, or deterring permission issues, is a great benefit to military operations and commercial interests. Before the use of satellite imagery, costly and time consuming methods such as side-scan sonar from a vessel or airborne radar were the only methods to assess the near coast bathymetry. With the use of commercial satellite data, time is saved by one quick remote scan versus a hydrographic survey that could take a month or two for a complete chart to be made. Operational considerations are reduced using satellite products. A full hydrographic survey, which involves vessel work and post processing, requires more logistics and manpower. Airborne imagery has a shorter collection time but still requires the some planning and logistics. Using satellites and capitalizing on their orbits for locations of opportunity require less personnel and operational management. The increasing resolution of commercial satellite imagers, the quick revisit time and the near global coverage of data has allowed an alternative method to producing useful bathymetry charts for remote locations where investing in a survey platform would be cost inhibitive.

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II. BACKGROUND

A. VISIBLE LIGHT TRANSMISSION BASICS

Deriving bathymetry from a satellite image is based on the physical properties of electromagnetic spectrum. As the solar irradiance reaches the earth's atmosphere, it is modified by scattering and absorption through atmospheric gases, aerosols and clouds. This modification reduces the amount of radiance that reaches the surface whether that is land or water. The albedo and other surface characteristics will define the radiance that is reflected back through the atmosphere (Figure 1). The top of atmosphere radiance collected by passive sensors on commercial satellites can be used for bathymetry calculations.

Figure 1. The solar irradiance transmission through the atmosphere.

When the solar irradiance reaches the ocean surface and transits through the water column, it is modified again as the water causes increased attenuation. This amount of attenuation is a function of the wavelength. Shorter visible wavelengths, like blue and green, will penetrate the water column to a deeper depth than longer wavelengths like a red and near IR (Figure 1). It is this difference in water penetration distance for visible

wavelengths that is exploited in the bathymetry derivations. Figure 2 displays the depth penetration of the visible light spectrum in ocean waters under ideal conditions. Using the measured top of atmosphere reflected radiance from an ocean source; scientists have been able to pull out the depth of the water column consistent with the radiance observed

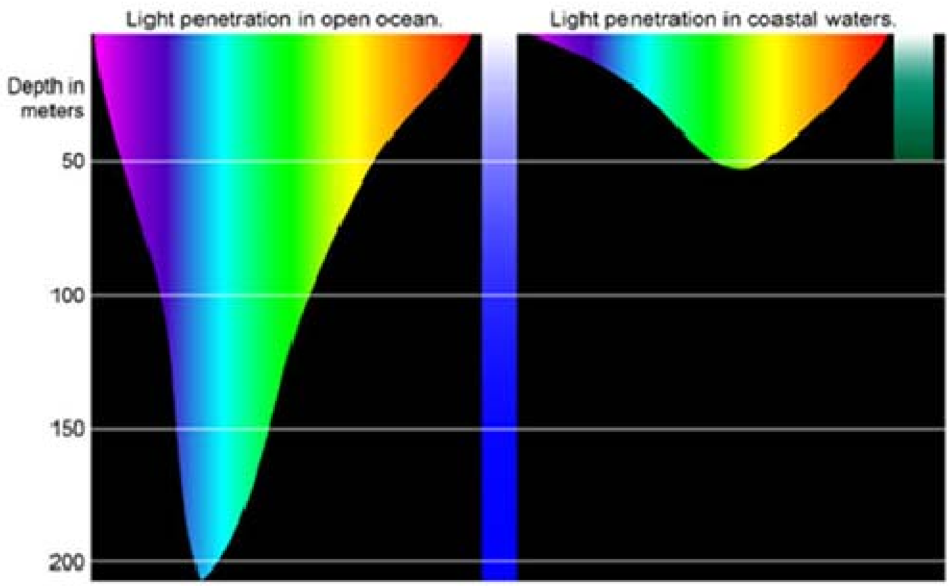

Figure 2. Visible Light Penetration in water. Shorter wavelengths such as blue and green penetrate the water column deeper than the longer wavelengths. (From Kyle Carothers, NOAA-OE, 2007)

B. PREVIOUS WORK IN SATELLITE DERIVED BATHYMETRY

The work of Stumpf et al. (2003) demonstrated the use and benefits of a wavelength ratio algorithm in comparison to other derived bathymetric algorithms. Using the water column attenuation as the main factor in determining the depth of the bottom, Stumpf et al. were able to apply their method to remote locations. Previous methods involved more parameters and in situ measurement of water properties (Lyzenga 1978, 1981, and 1985). Stumpf developed a method that uses very little input beyond the satellite multi-spectral image. The basic assumption of this ratio algorithm is that the water column attenuation is the dominate factor in the amount of water leaving radiance measured. The bottom type interactions are considered to be less significant for this calculation on the basis of both wavelengths in the ratio experiencing a similar

modification to their reflectance. Thus, the water leaving radiance measured by the satellite will predominately be a function of water column depth.

This ratio method derived by Stumpf et al. (2003) was designed to work in areas of limited access where little is known about the actual water column characteristics and in-situ measurements are unavailable. Using the wavelength dependency of attenuation in the water, Stumpf derived the ratio formula using reflectance of two wavelengths:

$$Z = m_1 \frac{\ln(nR_w(\lambda_i))}{\ln(nR_w(\lambda_j))} - m_0 \tag{1}$$

Where Z is the depth, m_1 is a calibration coefficient, $R_w(\lambda)$ is the water leaving reflectance per wavelength, n is a constant to keep the ratio positive and m_0 a correction term for zero depth. The ratio method is especially useful for areas of the world that traditional survey platforms cannot operate in or for providing a quick turnaround of a bathymetric product.

Several studies have addressed remote sensing of bathymetry using the ratio method. All used the water leaving radiance measured by an airborne or orbital sensor. Until the launch of DigitalGlobe's Worldview 2 (WV-2) satellite, scientific researchers had access to blue, green, red and NIR spectral bands from commercial satellites. WV-2 offers four additional bands to include a coastal blue, yellow, and a second near IR band.

Loomis (2009) used an airborne hyperspectral image of Kaneohe Bay, Hawaii in which the yellow band was used to test the added value of the yellow band anticipated for the WV-2 sensor. Loomis was able to demonstrate an increased accuracy when using the yellow wavelength band compared to Stumpf et al.'s original blue and green band ratio.

The ratio method has some deficiencies. Some studies have shown sensitivity to bottom type (Densham 2005; Clark 2005; Camacho 2006). Dark bottom types increased the error in the ratio method using the blue and green bands. Densham (2005) also demonstrated the benefit of a green and red band ratio in the more turbid waters in Plymouth Sound, England.

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III. DATA AND METHODS

A. DATA

1. Worldview-2 Satellite

A Worldview-2 multispectral image of Tampa Bay, Florida was provided for this research by the commercial imagery company DigitalGlobe. The Worldview-2 (WV-2) is the first commercial polar orbiting satellite with an 8-band multispectral imager. It was launched October 8, 2009 into a sun-synchronous orbit at an altitude of 770 km (DigitalGlobe 2009). On board there is a high resolution (50cm) panchromatic and lower resolution (2m) multispectral imager. The multispectral sensor provides 1.84 m resolution at nadir and 2.08 m at 20^o off –nadir. The swath width is 16.4 km. WV-2 provides the customary blue, green, red and near-infrared bands. The four additional bands are coastal, yellow, red edge and a second near-infrared (see Table 1). Figure 3 is the spectral response curve from WV-2 for all eight spectral bands and the panchromatic band (black curve).

Table 1. Worldview-2 Band Wavelengths. (From DigitalGlobe, 2009)

Band	Band width (nm)	Center Wavelength (nm)
Coastal (new)	401-453	427
Blue	447-508	478
Green	511-581	546
Yellow (new)	588-627	608
Red	629-689	659
Red Edge (new)	704-744	724
NIR 1	772-890	831
NIR 2 (new)	862-954	908

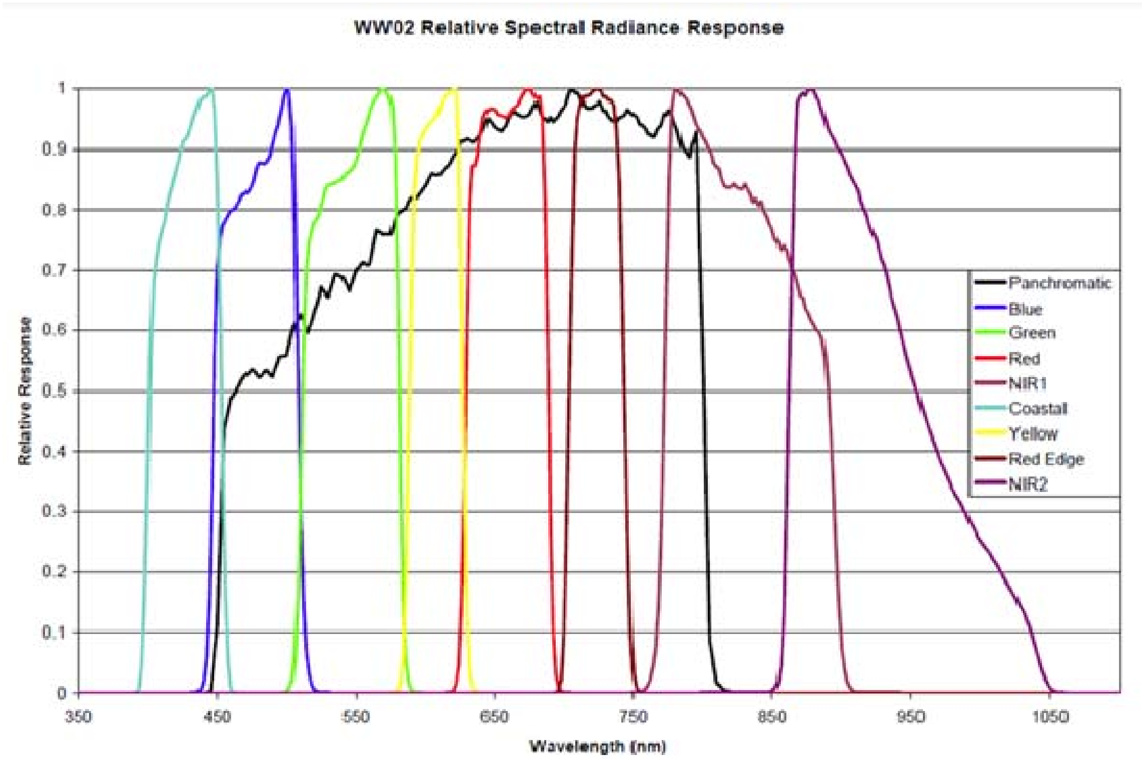


Figure 3. Worldview-2 Spectral Response Curve. (From DigitalGlobe, 2009)

a. Tampa Bay

The area under study is a 10 km square area (Figure 5) of Tampa Bay centered at 27° 34' 43.8''N, 82° 41' 25.7''W near Mullet, Egmont and Passage Keys at the entrance to Tampa Bay (Figure 4). Tampa Bay is located on the western side of the Florida peninsula and opens into the Gulf of Mexico. The cloud free image was taken on January 27, 2010 at 1625Z.

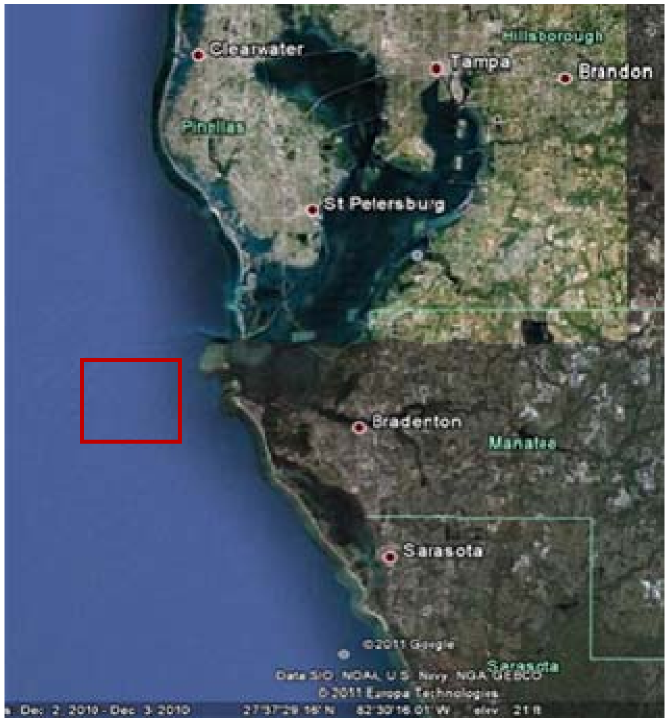


Figure 4. Tampa Bay, a portion of Florida and the Gulf of Mexico from Google Earth. The area coved by WV-2 data is highlighted by the red box.

Tampa Bay bathymetry is mostly unvarying with little change in the slope in the study area. There is a trench that is about 17m deep that crosses the study area from west to east and goes under the bridge. The rest of 10 km square-study area is less than 10m deep (Figure 6).

Figure 5. The Tampa Bay area of study. This is a RGB composite of TOA radiance from Worldview-2. The area in the red rectangle is the area where the transect lines were drawn near Fort de Soto County Park.

2. Digital Elevation Model

A digital elevation model (DEM) was acquired to use as ground truth for the satellite derived bathymetry. The DEM was completed by the United States Geological Survey (USGS) in 1996 (Figure 6). This hybrid elevation model was created from USGS topography and a National Oceanic and Atmospheric Administration (NOAA) bathymetry database using the best data available for Tampa Bay at that time. The NOAA data is sourced from 47 NOAA hydrographic surveys starting from 1945 to 1996. It has a horizontal spatial resolution of 1-arc-degree (30 meters) and referenced to the

NAD83 ellipsoid. This long period of surveys could lead to a more time invariant bathymetric data. In the merging of the elevation data to the bathymetric data, the DEM vertical data was changed to the GRS 80 ellipsoid.

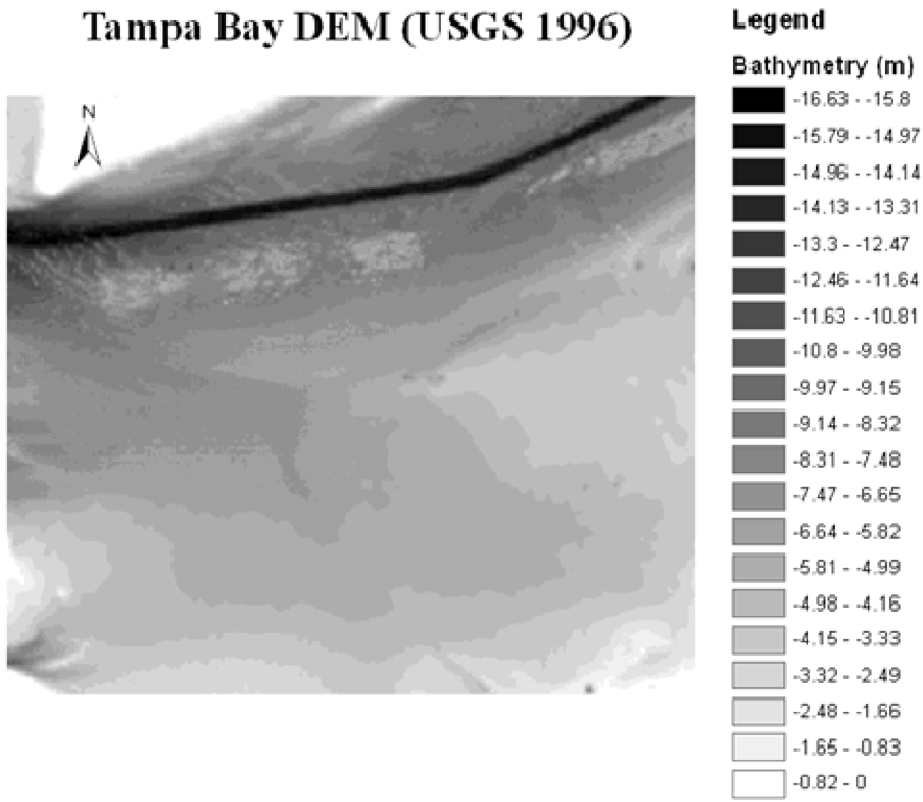


Figure 6. The USGS DEM of Tampa Bay using ArcGIS to select the same 10 km square grid as the WV-2 imagery. Most of the study area is less than 10 m deep. (From USGS 1996)

A more recent hydrographic survey (2001) of Tampa Bay is available from the USGS. This survey had a much higher sampling rate but did not have the same spatial coverage as the DEM (Figure 7). The hydrographic survey data points did not cover the area of interest, including reef areas. For the purpose of this study, transects were taken from the satellite derived bathymetry and compared to the same geo-located transects extracted from the DEM.

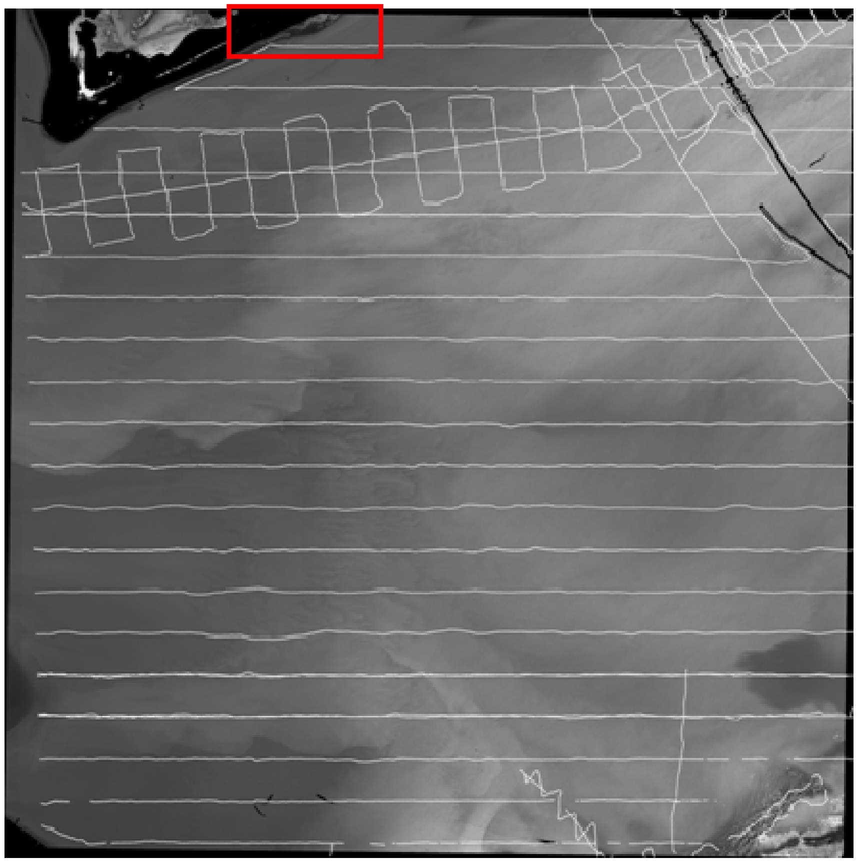


Figure 7. Hydrographic survey coverage (USGS 2001) of Tampa Bay compared to the coverage from the WV-2 satellite image. The red rectangle indicates the area of interest for the case studies. Background is of the blue/green relative bathymetry.

3. Bay Bottom Type Classification

Bottom substrate identification for this study was conducted by a visual observation of the WV-2 data in areas where the bay bottom was visible. Core samples of Tampa Bay were used to indicate bottom substrate in areas where the bottom was not visible. These cores samples were provided by the Gulf of Mexico Integrated Science Tampa Bay Study through the USGS. By observation of the WV-2 image near the transect lines, and for the purpose of this study, the yellow, tan or light brown areas with shaded wave-like features are classified as sand. The darker brown, reddish brown and black non-sand areas are defined as reef (Figure 8). Those areas classified as reef, indicate a bottom that does not appear to be sand, but could be composed of silt, mud,

rock, reef and vegetation, or a combination types. Areas in the deep water, where the bottom is difficult to observe, is classified as sand-like as indicated by the results of the core samples.

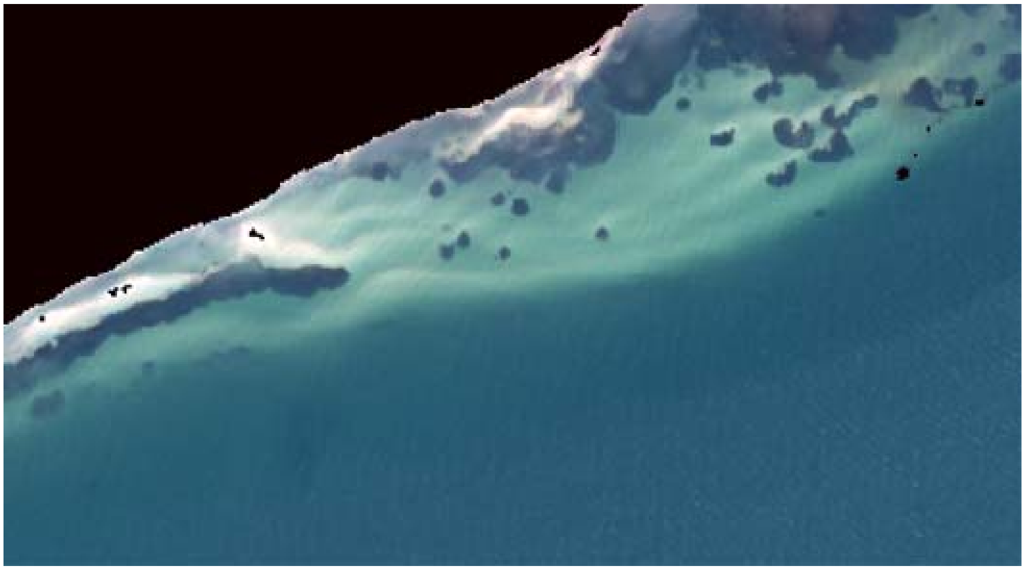


Figure 8. Bottom type identification by visual inspection. Areas that are light brown, yellow or tan and contain wave-like patterns are classified as sand. Areas that are noticeably darker brown, dark red or black and have rough edges or circular shape are classified as reef. Areas that are in the blue water and not visible are classified as sand by comparison to the core sample study from Gulf of Mexico Integrated Science Tampa Bay.

The core samples were collected in Tampa Bay from 2002 through 2005 and represent surface sediment of the bottom of Tampa Bay (Figure 9). These core samples are part of the Gulf of Mexico Integrated Science Tampa Bay study and were published by the USGS, Edgar et al. (2006). Of the 113 core samples collected and analyzed by Eckerd College Marine Geology Laboratory, only ten samples had a sand composition less than 60.0% with an average sand composition of 85.6%. The study only differentiates between coarse sand and gravel (greater than 63 cm or fine mud), silt and clay (less than 63 cm). Based on this core data in the Tampa Bay, it is assumed that those areas in this study, where the bottom is not visible in the satellite data, to be composed of coarse sand. The second most common bottom sediment is mud at 13.3%.

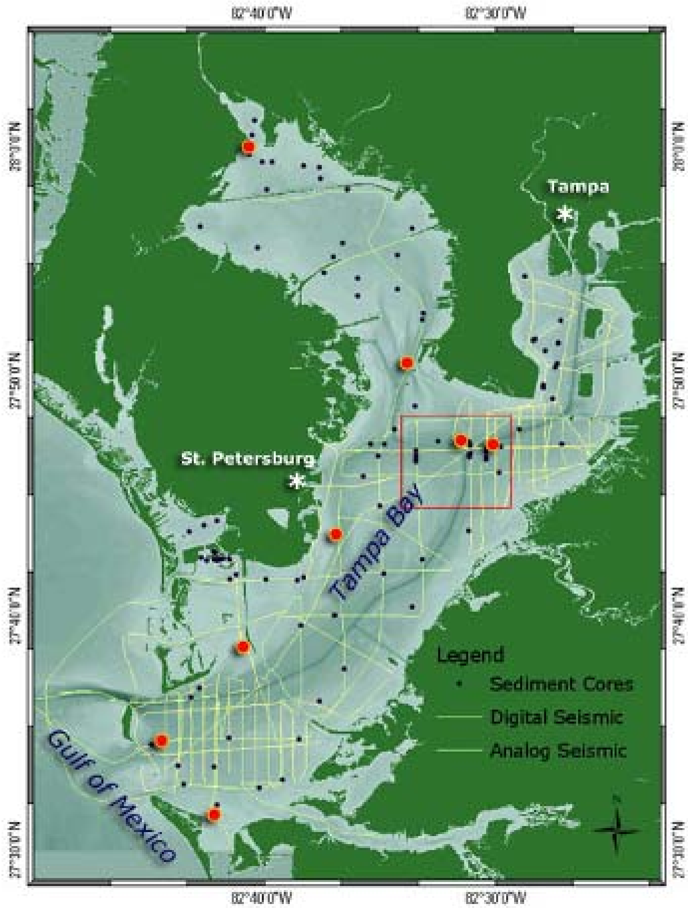


Figure 9. Core Sample locations from the Gulf of Mexico Integrated Science Tampa Bay study. (From USGS, 2006)

4. Tide Correction

Tide correction value was estimated from a NOAA tide prediction chart for Mullet Key Channel (Skyway), FL (Figure 10). The data was then interpolated for the time of the WV-2 collection. The result is a +0.38 m correction at 1625Z (1125L). For the tidal correction, the value of 0.38 m was subtracted from the derived bathymetry results to create the final bathymetry product for comparison to the DEM.

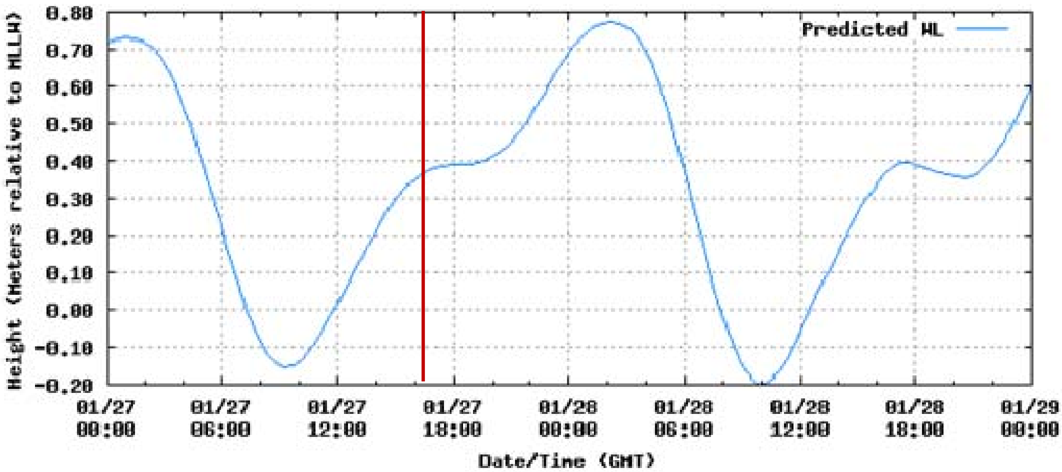


Figure 10. Tidal Prediction for Mullet Key Channel for 27 January 2010. The WV-2 collection time is 1625Z. The tide is predicted to be +0.38 m. (From NOAA, 2011).

5. Software

a. ENVI 4.5

The software package ENVI version 4.5 from ITT Visual Information Solutions was used on the WV-2 multispectral imagery to process and perform the TOA radiance, water leaving reflectance and derived bathymetry calculations. The ENVI ROI tool was used to create land, bridge and boat sections of the WV-2 image to be masked and to draw the transect lines for the comparison study. The ENVI software was also, able to upload the DEM data set and geo-reference it to the WV-2 image. Vectors could then be used to create the same transects in the DEM as were done in the WV-2 image.

b MATLAB 7.6.0 (R2008a)

The MathWorks software MATLAB version 7.6.0.324 (R2008a) was used to calculate the running mean of the WV-2 data once it was extracted into a data file from the transect line. MATLAB was used to generate all the plots of reflectance, the derived bathymetry and ground truth comparisons. The Curve Fit tool in MATLAB was used to conduct the linear regression of the data points for the last step in defining the m_1 and m_0 in Equation 1.

c. ArcGIS 10

Some of the work with the DEM data from the USGS involved utilizing ArcMap from the ArcGIS software created by ESRI. The original data set from USGS encompassed the entire Tampa Bay and beyond. The WV-2 data set only consisted of a small subsection of Tampa Bay. Using the upper and lower geographic coordinates from the WV-2 metadata, a cutout of the need DEM data was made, thus reducing the size of the data set to correspond to the area covered by the multi-spectral imagery.

B. METHODS

1. Derived Bathymetry Steps

This study followed the derivation steps outlined by Loomis (2009) with some modification and the addition of an atmospheric correction. Loomis outlined six basic steps for his work. These are the modified steps employed to reach the derived bathymetry result.

a. Step 1: Mask Land, Bridges, Piers and Boat Wakes

Using the observed characteristics of the NIR 2 band, which had a higher radiance value over the land than water, a radiance threshold of 110 was selected to create a ROI in ENVI. This procedure masked most of the land, bridges, piers and boats. Small portions of the boat wakes and bridges were still visible and had to be manually selected for masking (Figure 11).

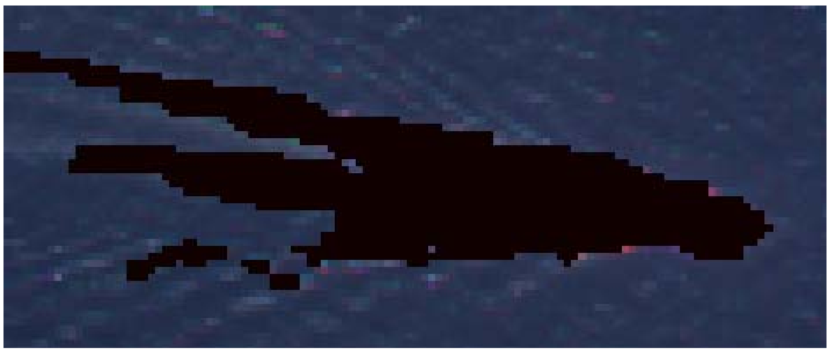


Figure 11. Boat mask example from the Tampa Bay data set. This is how the masked boat looks after the ROI threshold and the manual selection of pixels was completed.

b. Step 2: Convert the Satellite Digital Numbers to Top of the Atmosphere Radiance

The raw multi-spectral satellite data received from DigitalGlobe (2005) is in the form of digital numbers (DN). These DN values require a quick calculation using Equation 2 to change them into TOA radiance values.

$$L_{\lambda Pixel,Band} = \frac{K_{Band} \cdot q_{Pixel,band}}{\Delta\lambda_{Band}} \quad (2).$$

$L_{\lambda Pixel,Band}$ is the TOA radiance in units of W-m^{-2}-sr^{-1}- µm^{-1}, K_{Band} is the calibration factor for a given band, $q_{Pixel,band}$ is the DN and $\Delta\lambda_{Band}$ is the band width. The calibration factor for each band and the band width is included in the image metadata file (IMD) file that accompanies the multi-spectral data.

c. Step 3: Correct for Rayleigh and Aerosol Scattering Effects

The removal of aerosol radiance (L_a) was accomplished by a dark pixel subtraction method in the NPS Aerosol Retrieval Model (Durkee et al., 2000). The WV-2 NIR 1 and red bands over the dark water pixels in the Tampa Bay imagery were used to extract the radiance contributed by aerosol particles. The optical depth from the model for the different wavelengths are 0.34 (blue), 0.28 (green), 0.24 (yellow), and 0.23 (red). Once the aerosol scattering radiance was known for the red and NIR 1 bands, a curve was fitted to these points (Figure 12) and the corresponding radiance at the blue, green, yellow center wavelengths was subtracted from the TOA radiance. The equation for the mean aerosol scattering radiance is: $L_a = 9.17 / \lambda - 9.01$, the equation for the minimum aerosol scattering radiance is: $L_a = 7.66 / \lambda - 7.54$ and the equation for the maximum aerosol scattering radiance is: $L_a = 9.85 / \lambda - 9.32$.

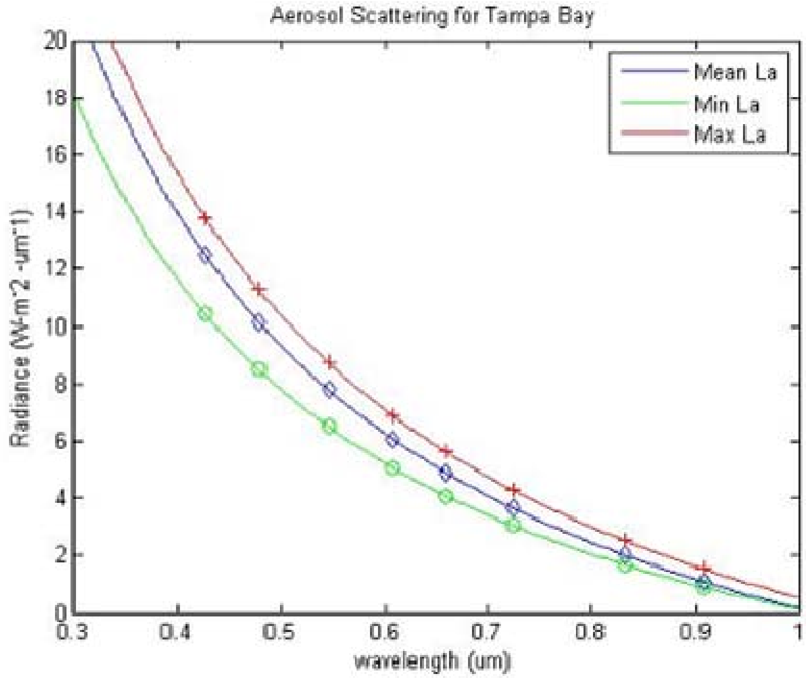


Figure 12. Aerosol scattering (L_a) curve for Tampa Bay created using the radiance of the red and NIR 1 bands calculated by the NPS Aerosol Retrieval Model. Wavelength in microns is on the x-axis and the y-axis is radiance in W-m^{-2}- µm^{-1}. Center wavelengths for each spectral band are indicated by the diamond point on the curve.

Using the derived radiance from NPS model to produce the red and NIR 1 band radiance, the Rayleigh scattering (Figure 13) curve is created. The equation for the curve is $L_r = 16.00 / \lambda - 17.60$. The Rayleigh scattering radiance (L_r) for each band's center wavelength is subtracted from the TOA radiance, along with the aerosol scattering radiance (L_a). The radiance that remains (Equation 3) is considered to be from the water surface (water leaving radiance, L_w) and represents the water column attenuation.

$$L_w = TOA - L_r - L_a \qquad (3)$$

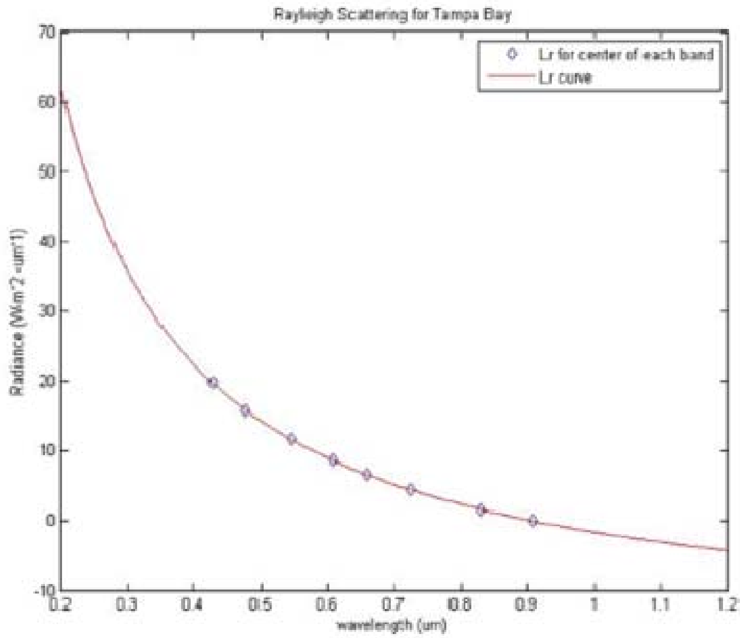


Figure 13. Rayleigh scattering (L_r) curve for Tampa Bay. Center wavelengths for each band are indicated by a blue diamond on the curve. Wavelength in microns is on the x-axis and the y-axis is radiance in W-m^{-2}- µm^{-1}.

d. Step 4: Change Radiance to Water Leaving Reflectance

The radiance (L_w) that remains after the subtraction of the L_a and L_r from the TOA radiance, is converted to water leaving reflectance, R_w, using equation 4.

$$\rho_{\lambda Pixel,Band} = \frac{L_{\lambda Pixel,Band} \cdot d_{ES}^{\;2} \cdot \pi}{Esun_{\lambda Band} \cdot \cos(\theta_s)} \qquad (4)$$

$\rho_{\lambda Pixel,Band}$ is the band-averaged reflectance, $L_{\lambda Pixel,Band}$ is the TOA radiance per band, $d_{ES}^{\;2}$ is the distance between the earth and sun at the time of collection, $Esun_{\lambda Band}$ is the solar irradiance and θ_s is the solar zenith angle. The information in the IMD file about the satellite and solar geometry at the time of the collection is used to calculate the water leaving reflectance. The TOA radiance used in Equation 4 is the Lw from Step 3.

e. Step 5: Calculate the Relative Ratio Bathymetry

The relative ratio is found by using Equation 5 (relative ratio depth), a segment of Equation 1 which creates a ratio between the spectral bands. This calculation is done to create five ratio combinations for this study. The first two are the original blue/green ratio, and the green/red ratio. The last three ratios are combinations with the new yellow band, a blue/yellow ratio, a green/yellow ratio and a yellow/red ratio. In each case the shorter water leaving reflectance wavelength $R_w(\lambda_i)$ is in the numerator and the longer wavelength $R_w(\lambda_j)$ is in the denominator.

$$\frac{\ln(nR_w(\lambda_i))}{\ln(nR_w(\lambda_j))} \qquad (5)$$

f. Step 6: Calculate Absolute Bathymetry

The relative ratios are used for a linear regression with known ground truth points. In this case, 40 DEM points were extracted with their corresponding ratio points. The linear regressions for all five ratio combinations can be found in the Appendix. The results of each regression are used to create the m_1 coefficient and m_0 constant for each ratio band. This results in the derived bathymetry for each ratio band. A correction is made for tides to complete the conversion to an absolute bathymetry depth in meters.

IV. RESULTS

Three case studies were selected for Tampa Bay. Case 1 examines the data from a segment of Transect 1 where there is an overall positive correlation of depth to relative ratio. The scatter plot of the relative ratio depth versus the DEM displayed a downward jump by two data points (Figure 20). Case 2 examines the visible wave-like pattern observed in the sand bottom segment of Transect 3. Case 3 examines the derived bathymetries from five ratio combinations and compares the results with the ground truth data provided by the DEM.

Three transect lines were drawn in the north section of the imagery near Fort de Soto County Park beach (Figure 5) for examination and a pixel by pixel comparison of the derived bathymetry to the bottom type and ground truth. These three transect lines were chosen based on their location in waters with little to no wave action and where the bottom is mostly visible (Figure 14). The along shore transect line, Transect 1 was chosen for its varying bottom type throughout the whole transect and relatively unchanging depth. Transect 2 was chosen for containing longer transect segments over sand and reef bottom types with a changing depth into deeper waters. Transect 3 was chosen as a perpendicular line to the shore with more coverage in the blue water and more depth change. In Transect 3, a separate investigation was conducted into the observed sand waves on the bottom (Figure 19) and whether the derived bathymetry had the sensitivity to reflect the pattern in the sand.

Five ratios were selected: blue/green, blue/yellow, green/red, green/yellow and yellow/red. The blue/green ratio is the original ratio used by Stumpf et al. (2003) and the green/red ratio is from Densham (2005). The red band attenuates more in the water and thus the derivable depth range is less than a blue/green derivable depth. The other three ratio combinations have the new yellow band added for the comparison study.

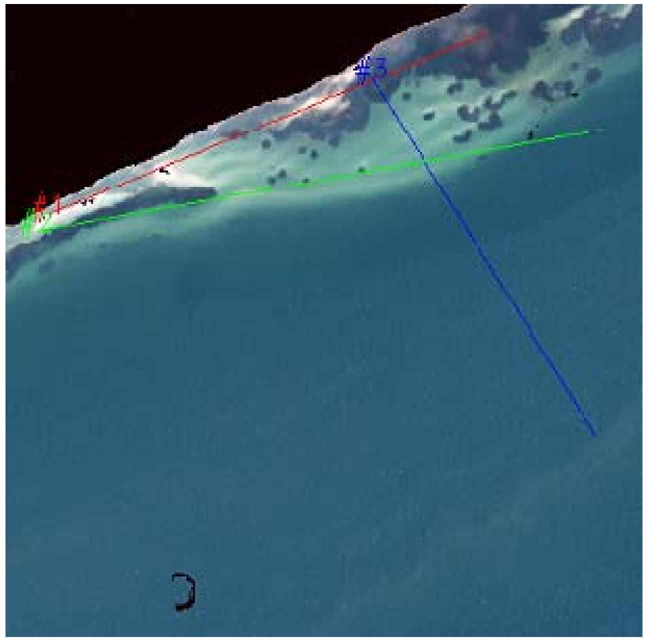


Figure 14. Overview of the three transects lines made for this study. This area is in the north part of the Tampa Bay data set, near Fort de Soto County Park. Background is a WV02 reflectance image with the land and boat masked.

A. TRANSECT LINE DESCRIPTION

1. Transect 1 Description

Transect 1 is a very near shore transect line that is 618 meter long and contains 287 pixel points. It travels from west to east over a shallow sand area (pixels 1:118) for 256 meters. This transect line then crosses into a mixed reef and sand area (pixels 119:192) for 161 meters before the last segment of Transect 1, which is over a dark reef, non-sand area (pixels 193: 287) for 201 meters (Figure 15). The reflectance along Transect 1 is shown in Figure 16.

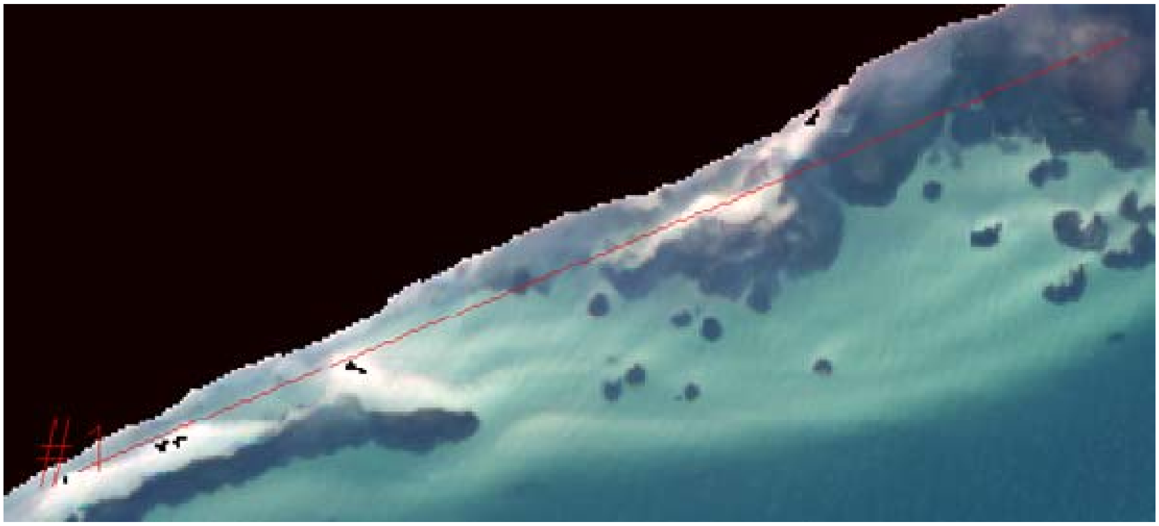


Figure 15. The along shore transect, Transect 1 (618m) overlaid on a RGB composite of reflectance.

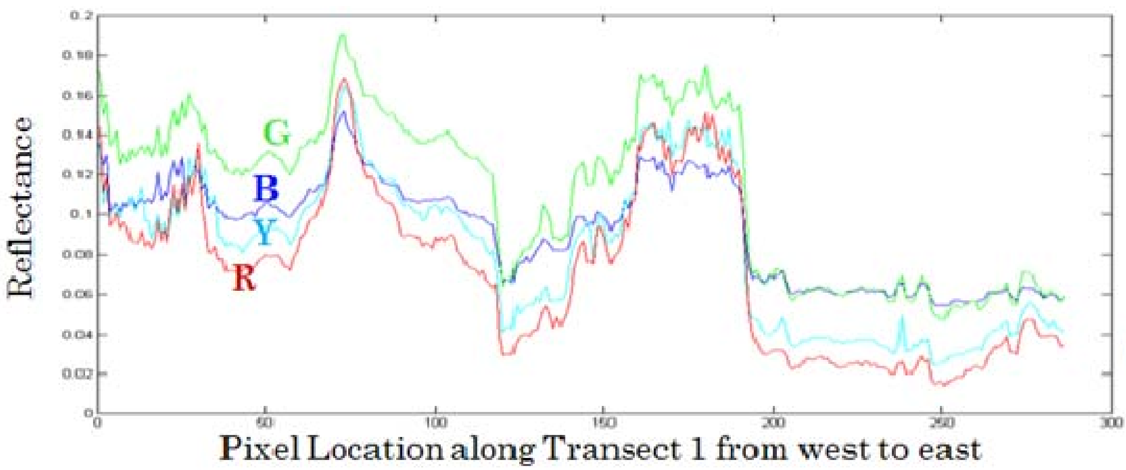


Figure 16. Reflectance along Transect 1 for four spectral bands, Green, Blue, Yellow (light blue line) and Red.

The DEM profile is generally flat with several small undulations. The DEM is shallow with a maximum depth of 0.66 meters for the entire transect. The average depth of the DEM is 0.30 m.

The reflectance profile of the four spectral bands (Figure 16) utilized for the ratio combinations displays the influence of the bottom type albedo. The peaks in the reflectance levels correspond to segments of the transect line that are over light sand.

The sand color also increased the yellow and red band reflectance so that it is higher than the blue band over the sand segments. The reef bottom type has the opposite effect on reflectance. There is increased absorption over the lower albedo of the reef areas and all four bands had significant drops in reflectance levels. A closer look at some of these lower reflectance segments display the yellow and red reflectance increasing and decreasing slightly based on the actual color of the reef bottom type. The overall reflectance levels of all the bands are at their highest levels compared to Transect 2 and Transect 3.

2. Transect 2 Description

Transect 2 runs west to east beginning near Transect 1 but skews more to the off shore area. It is 750 meters long and contains 370 pixel points. The visible bottom type of Transect 2 starts with light sand (pixels 1:9) and then crosses a shallow reef (pixels 10:60) followed by sand (pixels 61:93) and back over the reef (pixels 94:117). A much longer sand segment (pixels 118:299) has two small reef patches (pixels 172:178 and 211:214). The last segment of Transect 2 is characterized by the blue water observed (pixels 300:370) on the RGB reflectance composite (Figure 17). The reflectance along Transect 2 is found in Figure 18.

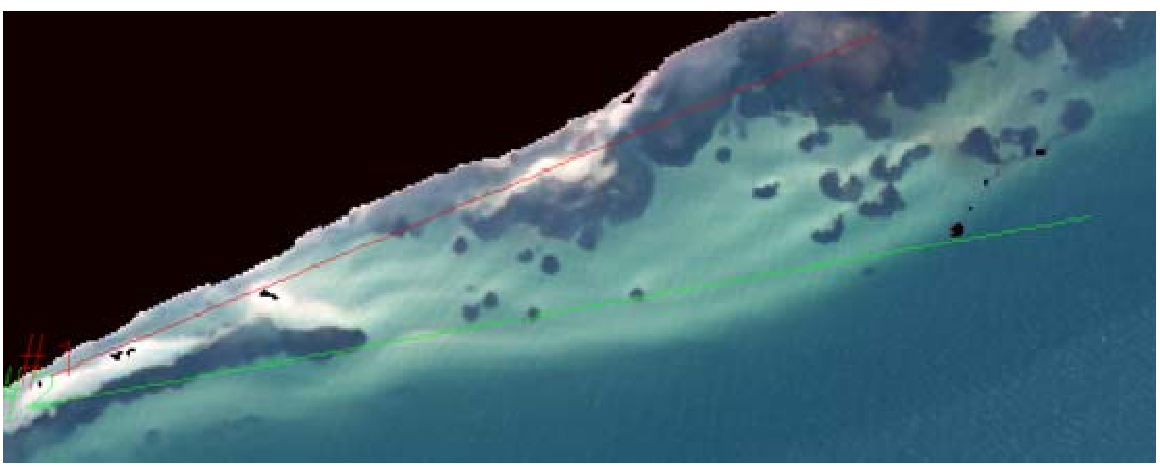


Figure 17. The skewed transect line, the green Transect 2 (750m) overlaid on a RGB composite of reflectance.

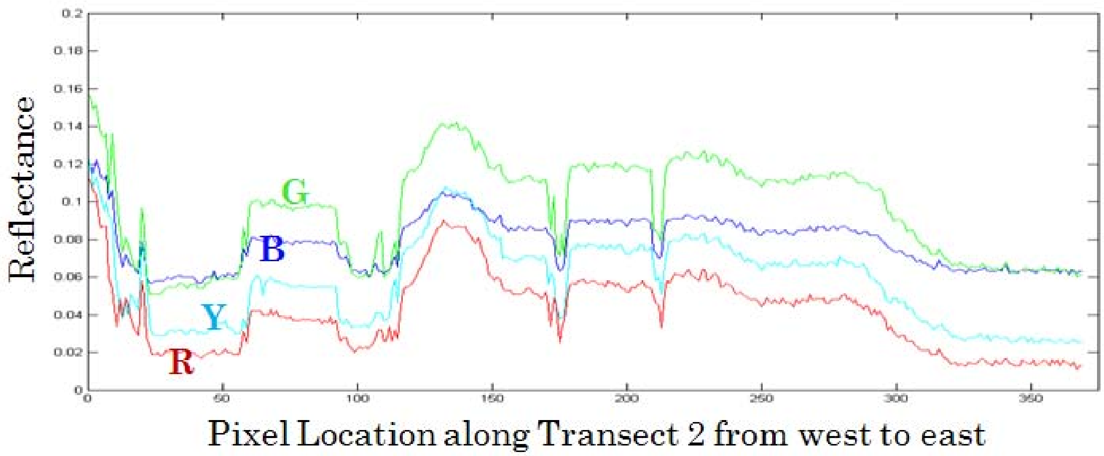


Figure 18. Reflectance along Transect 2 for four spectral bands, Green, Blue, Yellow (light blue line) and Red.

The reflectance profile of the four spectral bands for Transect 2 (Figure 18) has similar patterns as Transect 1. The light sand albedo has corresponding peaks in the reflectance. Drops in reflectance are noted where Transect 2 crosses over the dark reef segments. Even the small reef patches have this same impact. The difference between the reflectance of each band remains mostly constant through the transect line, unlike Transect 1 where the bands cross more often. The yellow band reflectance level gets above the blue band once at pixels 125–140. Over the reef segments, the blue and green band values converge as the absorption and lack of blue and green color in the reef affect the reflectance. After the peak at the beginning of the transect line, the overall reflectance levels of all the bands are comparable to Transect 3 and lower than Transect 1, indicating that information on the depth of the water column is present.

3. Transect 3 Description

Transect 3 is a 552 meter long (235 pixel points) transect line that runs from north to south (Figure 19), perpendicular to the shore containing. The first 40 meters of Transect 3 are over reef (pixels 1–17), followed by 117 meters over visible sand (pixels 18–67). The last 395 meters is blue water (pixels 68–235). The reflectance found along Transect 3 is plotted in Figure19 (b).

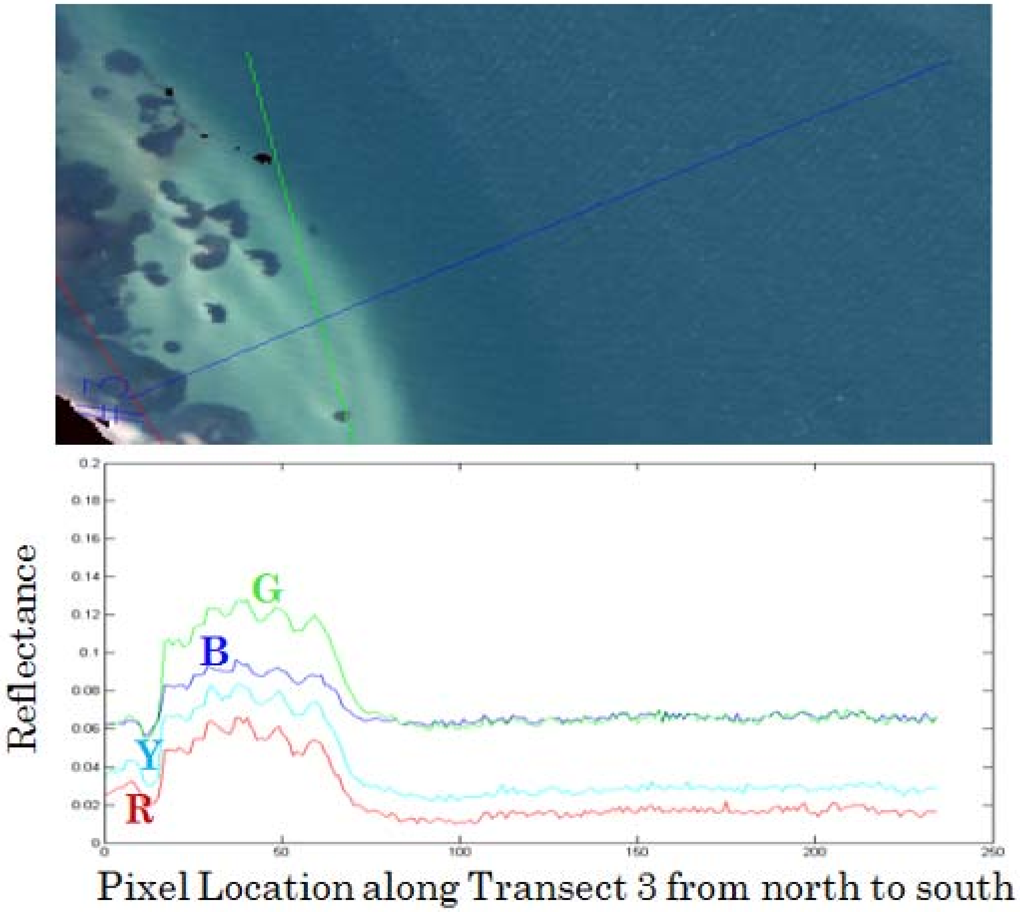


Figure 19. (a) Transect 3 (blue line) a north to south transect line overlaid on a reflectance RGB composite image. (b) Reflectance along Transect 3 for four spectral bands, Green, Blue, Yellow (light blue line) and Red.

The reflectance levels for Transect 3 (Figure 19) have a similar pattern that was observed in Transects 1 and 2. Over the sand segment there is a peak in the reflectance but not enough that the yellow band rises higher than the blue. Over the reef and blue water segment, the blue and green reflectance levels merge. The green band is the highest over the sand. The overall reflectance levels of all the bands are lower than the levels from Transect 2 and Transect 1.

B. CASE STUDY 1: RELATIVE RATIO BATHYMETRY COMPARISON

1. Description

Over the dark reef bottom type segment of Transect 1 (pixels 193: 287) there is an overall trend that demonstrates good correlation between relative ratio depth and the ground truth. There are two noticeable points where the relative ratio values drop significantly near 0.6 m depth (Figure 20). For this case study, these two points (pixels 267 and 277) are investigated as to the cause of the drop in relative ratio while the bottom type is still classified as reef.

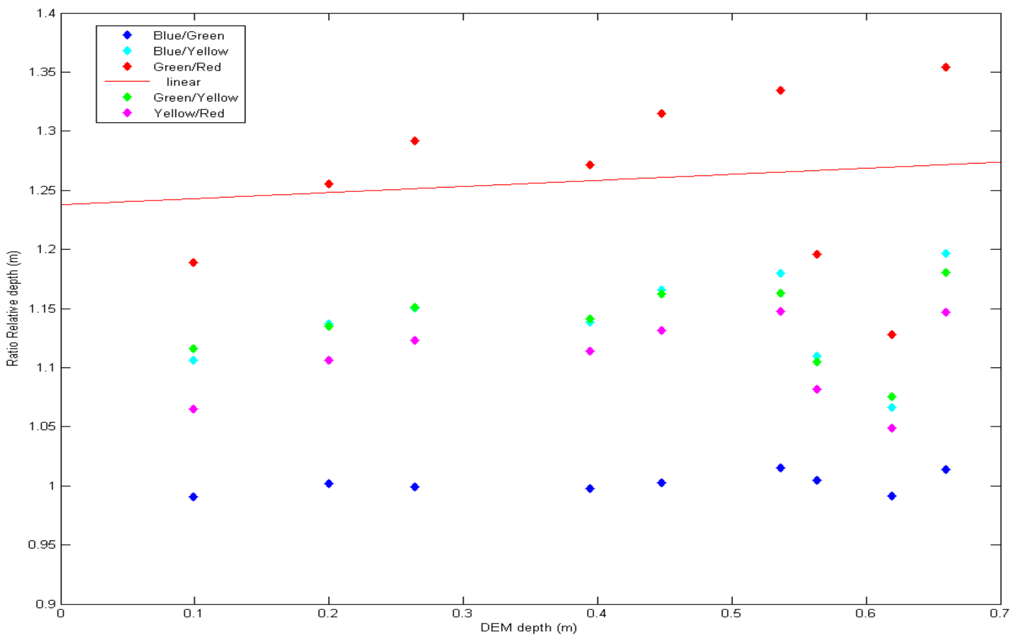


Figure 20. Ratio relative depth versus DEM depth from reef segment (pixels 193:287) of Transect 1. The two green/red ratio pixels in question are near the 0.6 m mark on the x-axis. The green/red ratio is red, the green/yellow is green, the blue/yellow is light blue, the yellow/red is magenta and blue/green is blue.

Four relative ratios are studied. The blue/green ratio was not examined since it was relatively insensitive to depth. The two points that dipped in relative ratio are identified as the last two points from the DEM transect (points 28 and 29), which correspond to pixel points 267 and 277 along the WV02 data transect line (Figure 21). Notice that while the DEM increased in depth along this entire segment, the green/red

ratio did as well, until the last two points where there is a reduction in relative ratio value that does not correspond to a similar change in ground truth.

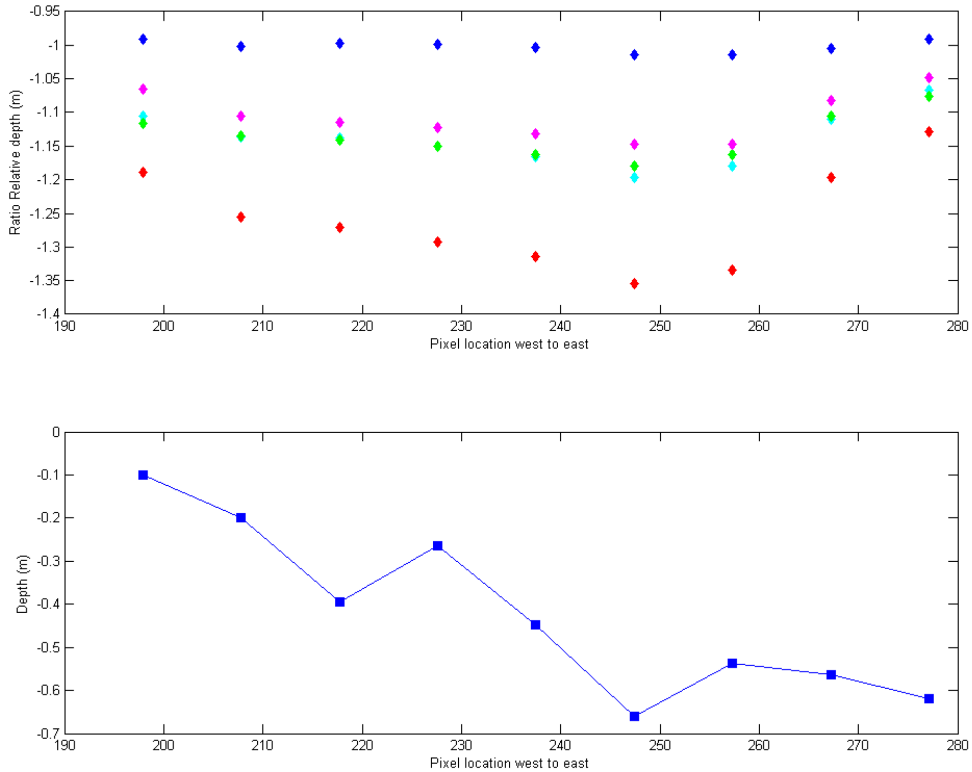


Figure 21. Reef bottom type segment of Transect 1. Relative ratio bathymetry on the top plot (a) with pixel location on the x-axis. The relative ratio is made negative for a better comparison with the DEM. The green/red ratio is red, the green/yellow is green, the blue/yellow is light blue, the yellow/red is magenta and blue/green is blue. The DEM depth is on the bottom plot (b) for comparison.

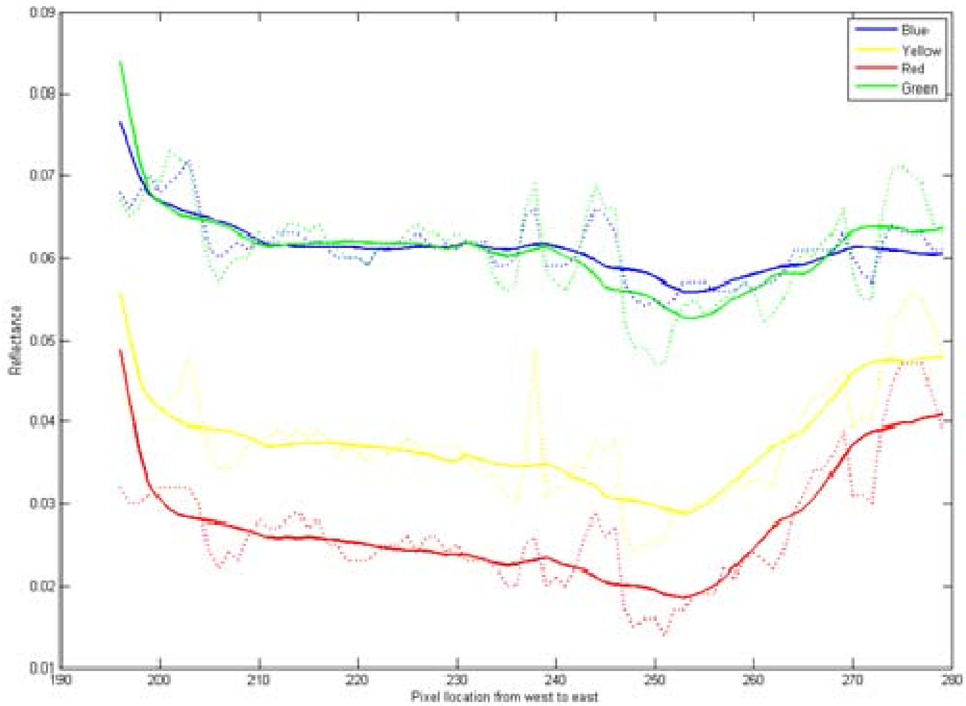
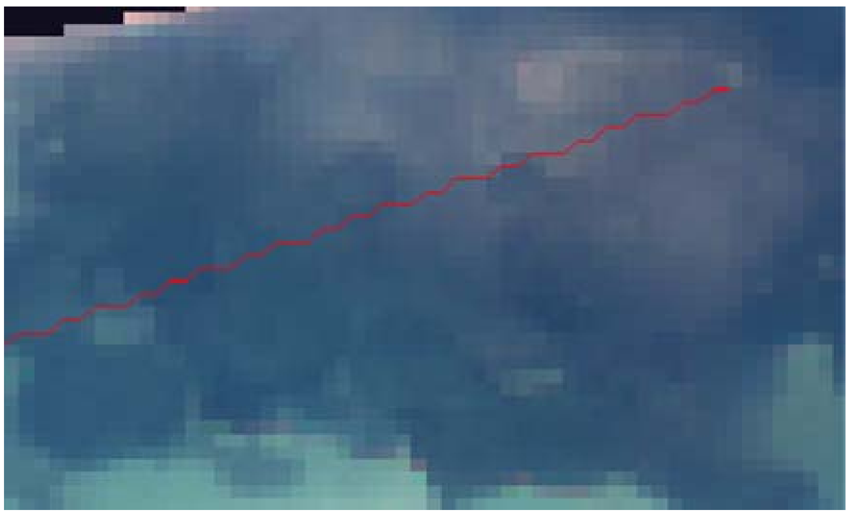


Figure 22. The reflectance for blue, yellow, green and red bands for the reef bottom type segment of Transect 1. The solid line is a running mean applied to smooth the data. The dotted line is the WV-2 reflectance for each pixel.

2. Case Study Discussion

The lower relative ratio values at pixel point 267 and 277 (Figure 20) could be caused by either a loss of water leaving reflectance in the numerator of Equation (1) and/or an increase of water leaving reflectance in the denominator. The green, yellow, blue, and red band reflectance running mean values are increasing (Figure 22) at the end of the plot. The blue band has the least noticeable increase from pixels 250 to 270 compared to the green, yellow, and red bands. The red band increases more than the green band, causing the green/red ratio to decrease. This also occurs with the blue/yellow and the green/yellow relative ratio, where the yellow band has increased more than the blue or the green bands. This provides a lower relative bathymetry result (i.e., shallower depth) in the green/red ratio, the blue/yellow ratio, the yellow/red, and the green/yellow.

The green/red, blue/yellow, green/yellow and yellow/red relative ratio decrease occurs were the bottom type pixels are lighter and more brownish red than the surrounding reef structure, as observed on the magnification of the RGB reflectance composite image (Figure 23). At pixel 277, the green, yellow, and red reflectance bands have reduced their rate of change (running mean slope) to appear to be leveling off. Both bands are at higher reflectance values than they were for most of the reef segment (pixels 193:287). The red and yellow bands did increase their reflectance value more than the green or the blue bands did during this segment.


(a)

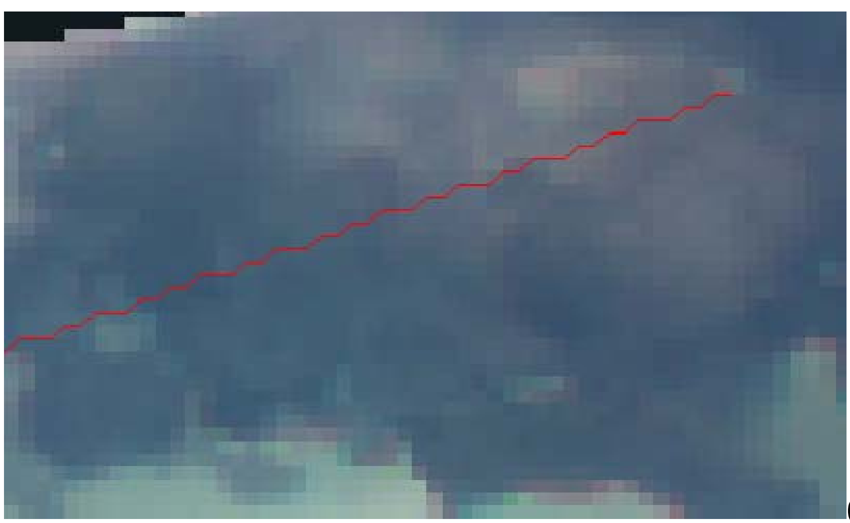

(b)

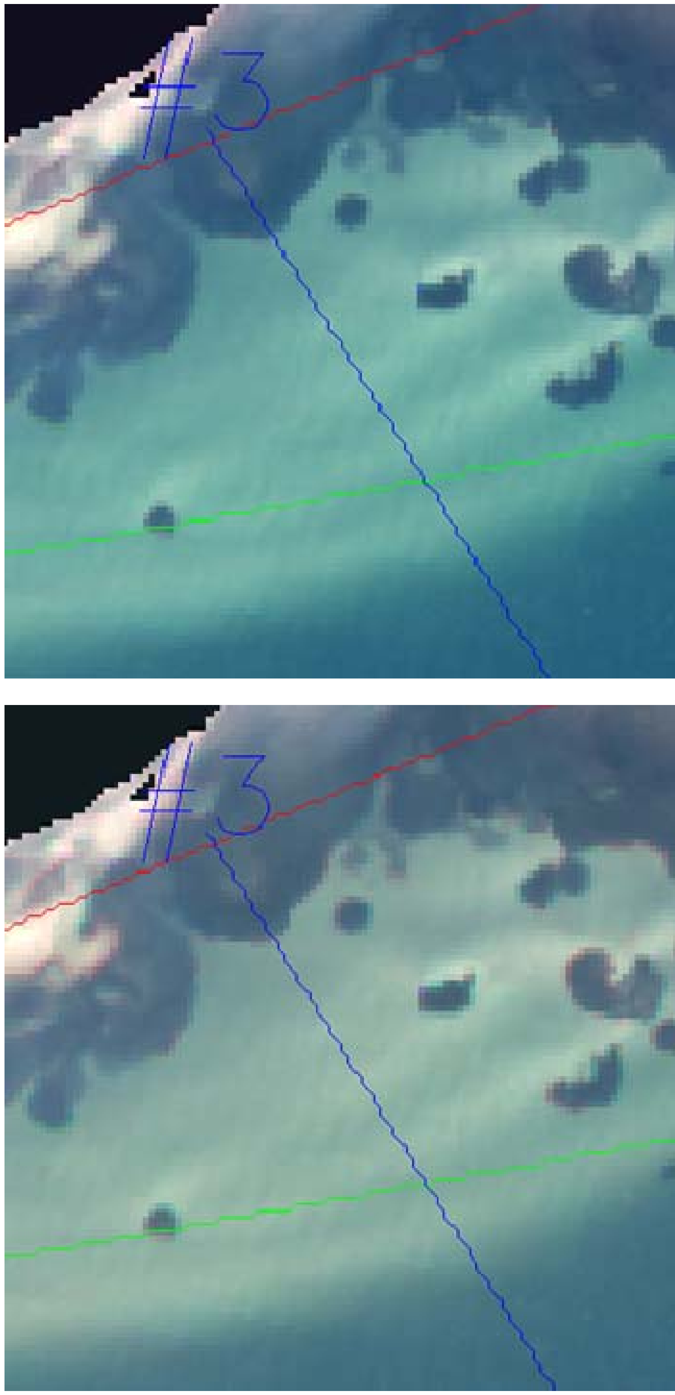
Figure 23. A magnification of the last 103 meters (48 pixels) of Transect 1 over the reef bottom type. A RGB reflectance composite is on top (a) and an YGB reflectance composite is the bottom (b).

The yellow/red relative bathymetry is the smallest ratio value of the four compared in this case study. Though the five relative ratios decrease in depth towards the end of Transect 1, (pixel 257 to 277) the greatest depth change is observed by the green/red relative bathymetry (Figure 21). By examining the reflectance values that went into the relative bathymetry calculations, the bottom type coloration can be found to influence the increase in reflectance values of certain bands, namely the yellow and red bands. This is the result of the dark reef segment becoming more reddish brown as observed around pixel 277 (Figure 23). The peak reflectance of the red, yellow and green bands reflect the lightest part of the reef pixels along Transect 1. The darker pixels to the west (left) of pixel 277 have a corresponding dip in the reflectance values near 270, demonstrating the sensitivity of the color of the bottom to the water leaving reflectance.

C. CASE STUDY 2: SAND WAVES IN TRANSECT 3

The sand segment (pixels 18:67) of Transect 3 is 116 m long and is observed with visible light and dark sand patches. The light and dark coloration are suggestive of a wave-like pattern on the bottom (Figure 25). The three defined sand waves for this case study are centered at pixels 43 (37–47); 53 (48–59); and 63 (60–67). The sand waves are examined, pixel by pixel, in the bathymetry profile plot (Figure 25). The sand waves are 25 meters in length or about 12.5 pixels in the WV-2 reflectance image. This feature is too small to be seen in the DEM due to the DEM lower resolution (30 m per pixel).

The sand waves are likely to be transitory in nature and not found on the DEM, if the resolution could support it. The sand waves would be removed by the running mean calculation so only the unsmoothed WV-2 data is used for contrast. Case study 2 is an examination of the sensitivity of the derived bathymetry calculation to apparent changes in the color of the sand and any corresponding depth changes.



(a)

(b)

Figure 24. Magnification of Transect 3 (blue line) over the 116 m sand segment (pixels 18:67) where the shading indicates a wave-like pattern in the sand. The top (a) figure is a RGB reflectance composite and the bottom (b) figure is an YGB reflectance composite.

1. Case Study Discussion

The derived bathymetry profiles (Figures 25 and 26) show a brightness variation consistent with bathymetry variations. In segments of rising bathymetry, the sand is brighter and a drop in bathymetry appears darker. This pattern is most noticeable in the blue/green ratio, and is observed for all three defined 25 m sand waves. There still seems to be the trend of the light sand side of the wave producing a shallower upslope profile and the darker sand side producing a deeper negative slope result. The blue/yellow derived bathymetry has a similar trend in its profile pattern, as well, but the ratio appears to visually represent the sand waves better than the blue/green derived bathymetry (Figure 27b). To lesser extend the green/yellow (Figure 27d), and the green/red (Figure 27c) ratios also have a wave in the bathymetry near the center points of the sand waves, but it is muted and not discernable by a glance at the profile plot (Figure 25).

The first two sand waves (pixels 37–47; and 48–59); are the most consistent in the ratios and the last wave (pixels 60–67) tends to merge with the downward slope in Transect 3. The defined waves appear deeper corresponding to the DEM. The last wave is on the edge of the dark blue bottom type segment and drops to a deeper bathymetry. It is hard to discern the exact nature of this wave in the ratio bathymetry.

There are other variations in the water leaving reflectance (Figure 19b), characteristics of the bottom type and water column that hide the sand waves. These oscillations affect the derived bathymetry and the variability is still present in the profile. The sand waves are not obvious to a causal glance of the blue/green derived bathymetry or any of the other ratios. They are even lost in other ratios such as the yellow/red when compared to the bathymetry profile plot (Figure 25) or the imagery (Figure 26).

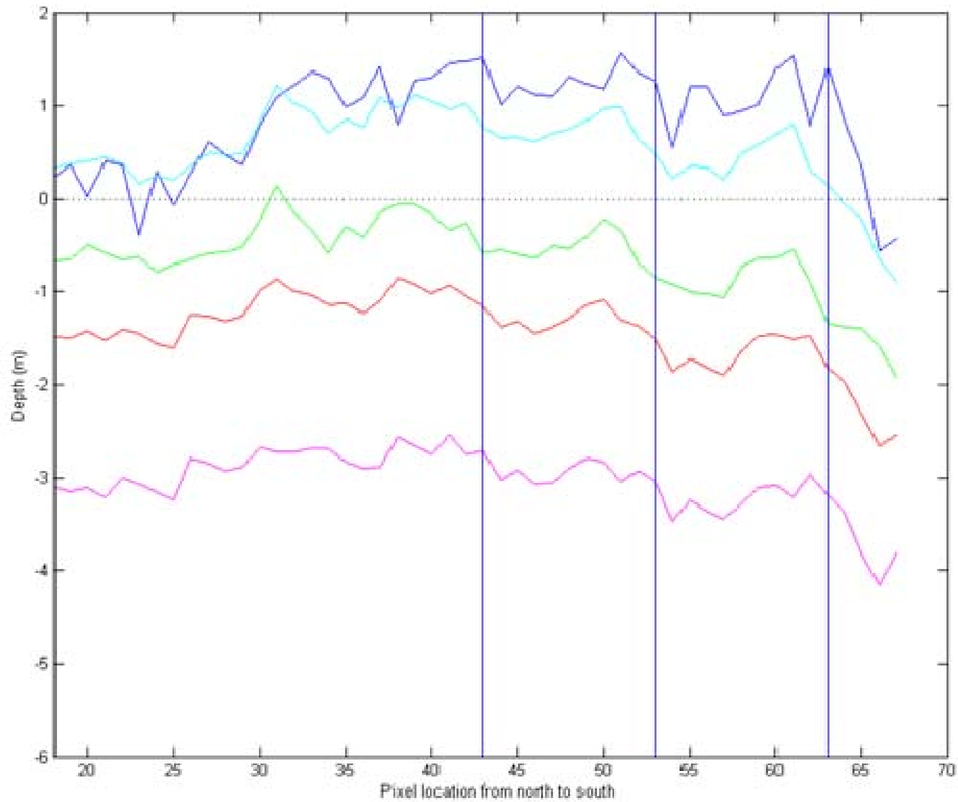


Figure 25. A portion of the sand segment of Transect 3 where the sand waves are visible. All five ratio absolute bathymetries are compared. The blue/green ratio is blue, the blue/yellow is light blue, the green/yellow is green, the green/red is red and the yellow/red is magenta. Depth is the y-axis and the pixel location is the x-axis. The defined sand wave crest axis' are pixels 43, 53 and 63.

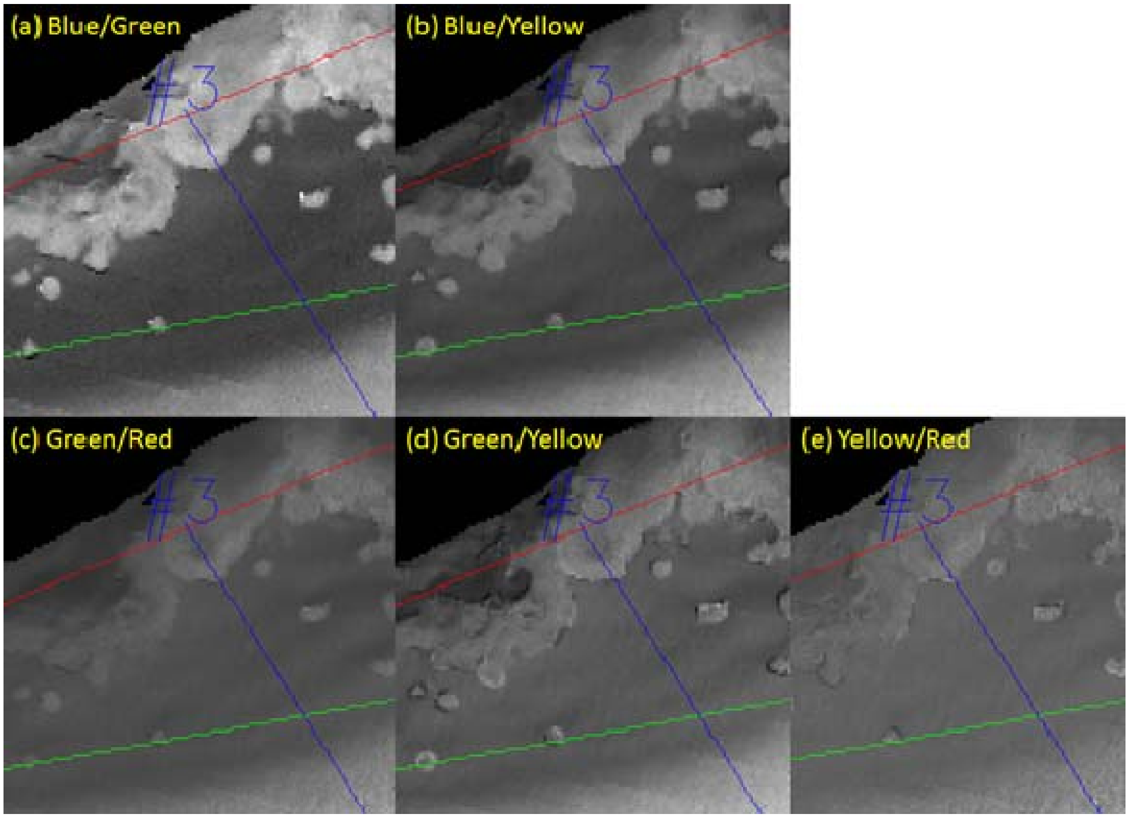


Figure 26. A comparison of the blue/green (a), blue/yellow (b), green/red (c), green/yellow (d) and yellow/red (e) derived bathymetry in the sand segment of Transect 3 (blue line). The wave like pattern is most visible in the blue/yellow and green/yellow. It is less evident in the blue/green, the green/red and the yellow/red derived bathymetries.

D. CASE STUDY 3: ABSOLUTE DERIVED BATHYMETRY COMPARISON

In this case study, all three transect lines are compared using the five ratio derived bathymetries, the DEM and the bottom type. This is an investigation into how well each ratio, specifically those using the yellow band, handled the bottom type influences in comparison with the DEM profile as the ground truth standard.

1. Transect 1 Derived Bathymetry Comparison

Both the blue/green and the green/red derived bathymetry reveal several segments along Transect 1 (Figure 27), where its profile is of similar depth and slope as the DEM. This occurs over the sand and mixed bottom type segments of Transect 1 in which the sand is a shade darker than other sand segments. The green/yellow, blue/yellow, and the

green/red bathymetries are closest to the DEM when Transect 1 is over darker bottom types such as the reef area. In the last reef segment, the green/red bathymetry profile was very similar to the blue/yellow.

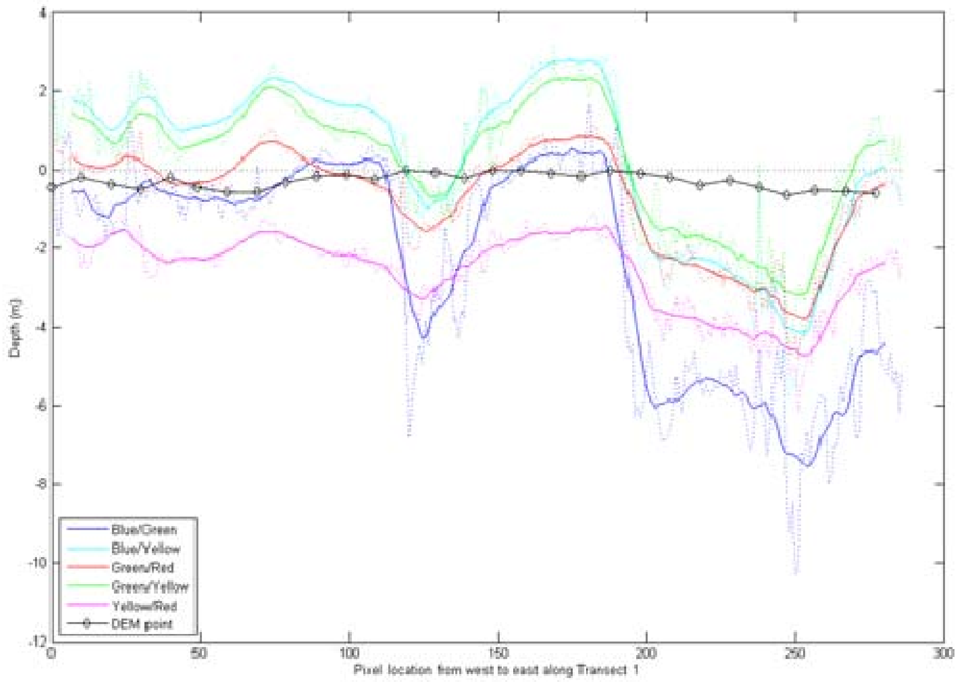


Figure 27. Transect 1 absolute bathymetry compared to the DEM (black diamond line). The dotted black line is the sea level line. The solid lines are the running mean of each data set. The blue/green ratio is blue, the blue/yellow is light blue, the green/yellow is green, the green/red is red and the yellow/red is magenta. Depth is the y-axis and the pixel location along the transect line from west to east is the x-axis.

The blue/green, green/red, and yellow/red ratios over the lighter sand and the reef segments have more error when compared to the DEM. The blue/green derived bathymetry reports the deepest depths over the dark reef segments, dropping deeper than the yellow/red ratio. The blue/green ratio profile is deepest at the end of Transect 1 where it drops to 5.75 to 7.99 m over the dark reef bottom type. The reef has low albedo reducing the blue and green band reflectance (Figure 16). Over the reef the blue and green band reflectance merge creating a ratio of similar reflectance levels, similar to the

yellow/red ratio that has a ratio between two similar reflectance levels. Both the yellow/red and blue/green have some of the greatest difference compared to the ground truth (Figure 28).

The green/yellow and blue/yellow derived bathymetry is well above the DEM for most of Transect 1. They even produce results of +2.7 to +2.5 m above sea level in some of the sand segments. Only when the transect line is over the dark reef bottom type does the green/yellow, blue/yellow become the profiles closest to the DEM. This is unusual when compared to the other transect lines where green/yellow and blue/yellow do not have this pronounced difficulty over sand. This could be caused by the overall increase of yellow (sand) reflectance with the high albedo and very shallow water column depth. Transect 1 has the overall highest reflectance levels for all bands (Figures 16, 18, and 19).

The yellow/red bathymetry is consistently well below the DEM depth and has less depth change over the varying bottom type in Transect 1. The sand segments do not appear to have as much of an impact on the yellow/red bathymetry as it did to the other ratios. The yellow/red bathymetry over the sand is the deepest profile and is several meters deeper than the DEM (Figure 27).

The difference plot displays the difference between each calculated bathymetry profile and the DEM (Figure 28). The yellow/red ratio has a consistent difference. The blue/green and green/red ratios display a sensitivity to the bottom type. Depths are close to the DEM over sand and several meters deeper when over darker surfaces. The green/yellow and blue/yellow ratios show similar emergent (above water level) profiles.

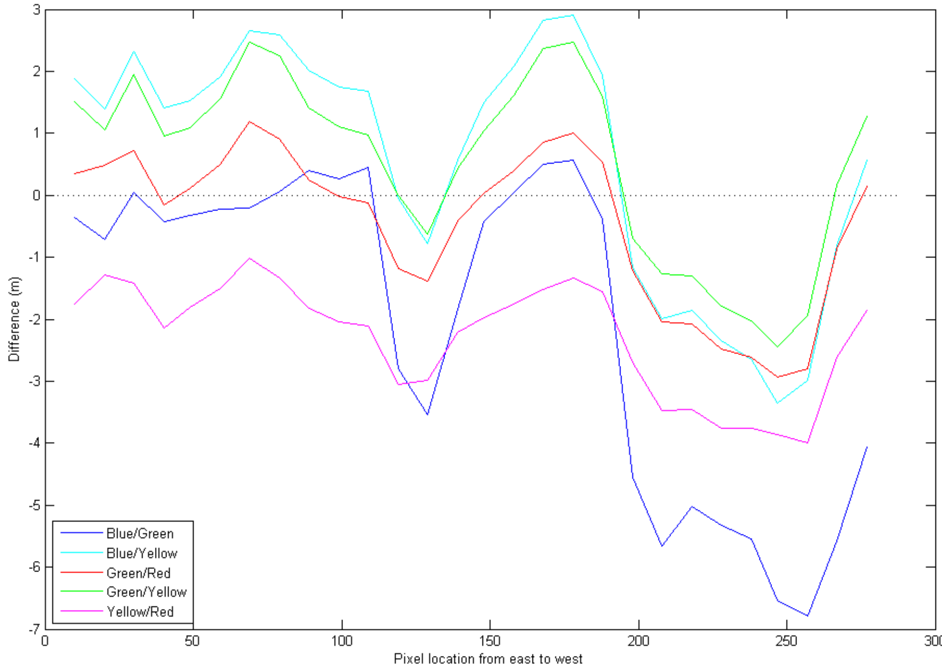


Figure 28. The difference between the derived ratios and the DEM along Transect 1. The difference was only taken at the corresponding DEM and ratio points from the smoothed data. There are 29 DEM points for Transect 1. The depth difference is the y-axis and the pixel location from west to east is the x-axis.

2. Transect 2 Derived Bathymetry comparison

The DEM profile for Transect 2 is shallow, remaining under 3 meters for the entire transect. For the first three quarters of the DEM profile, the depth remains fairly constant between 0.6m and 1.2m before having a negative slope for the last quarter where it reaches a depth of 2.8m.

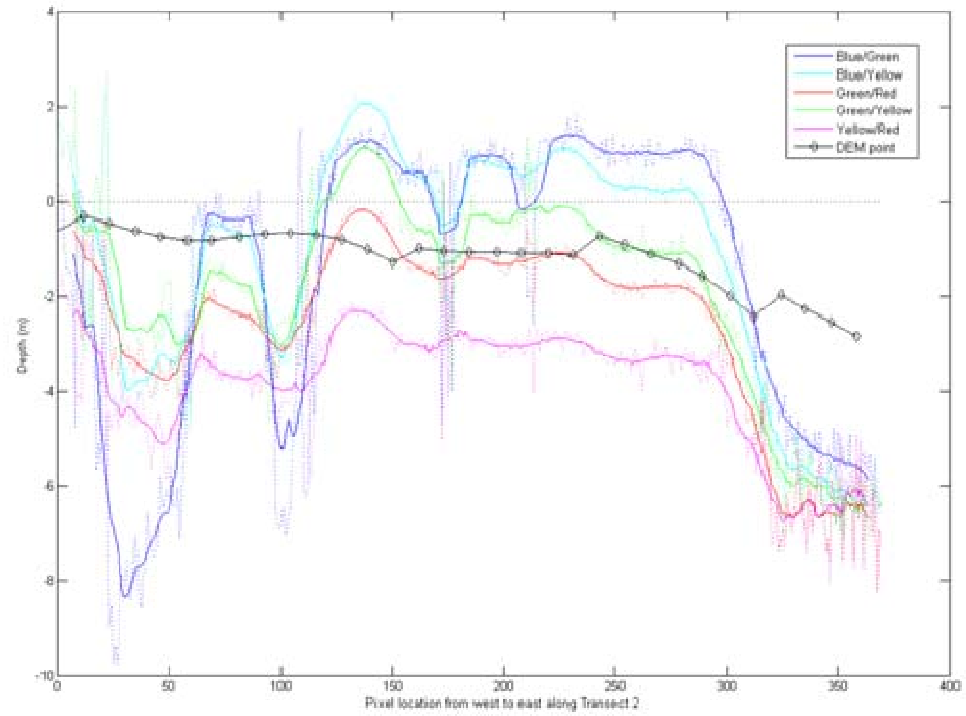


Figure 29. Transect 2 absolute bathymetry compared to the DEM (black diamond line). The dotted black line is the sea level line. The solid lines are the running mean of each data set. The blue/green ratio is blue, the blue/yellow is light blue, the green/yellow is green, the green/red is red and the yellow/red is magenta. Depth is the y-axis and the pixel location along the transect line from west to east is the x-axis.

Some of the same patterns (Figure 29) appear in Transect 2 as in Transect 1. The reef bottom type tends to produce ratio bathymetry results that are deeper then the DEM. The blue/green derived bathymetry has noticeable trouble over areas of dark reef where the reflectance of the blue and green bands dropped and even merged (Figure 18). The blue/green reports its deepest depths over the reef bottom types reaching 8.3m (pixel 31) and 5.2m (pixel 101).

Over sand segments, the increased reflectance brought on by the higher albedo is still a factor. The blue/green ratio is closest to the ground truth over the shaded sand segment (61:93) between the reef segments (Figure 30), but then the blue/green profile becomes emergent over the other sand segments. The green/red and green/yellow bathymetry profiles follow the DEM profile the best in the longer and lighter shaded sand

segment after the reef segment. At times, either the green/red or green/yellow derived depths are almost the same as the DEM, starting after pixel 150. All ratios have a descending trend similar to the DEM in the last portion of the sand segment before the transition to the blue water segment. The slope over the sand into blue water segment displays the increased water column attenuation that is affecting all the spectral bands. The sand's albedo is still contributing to the results, as the green/red and green/yellow ratio profiles are still the closest to the DEM in this segment and other ratios are above the water level.

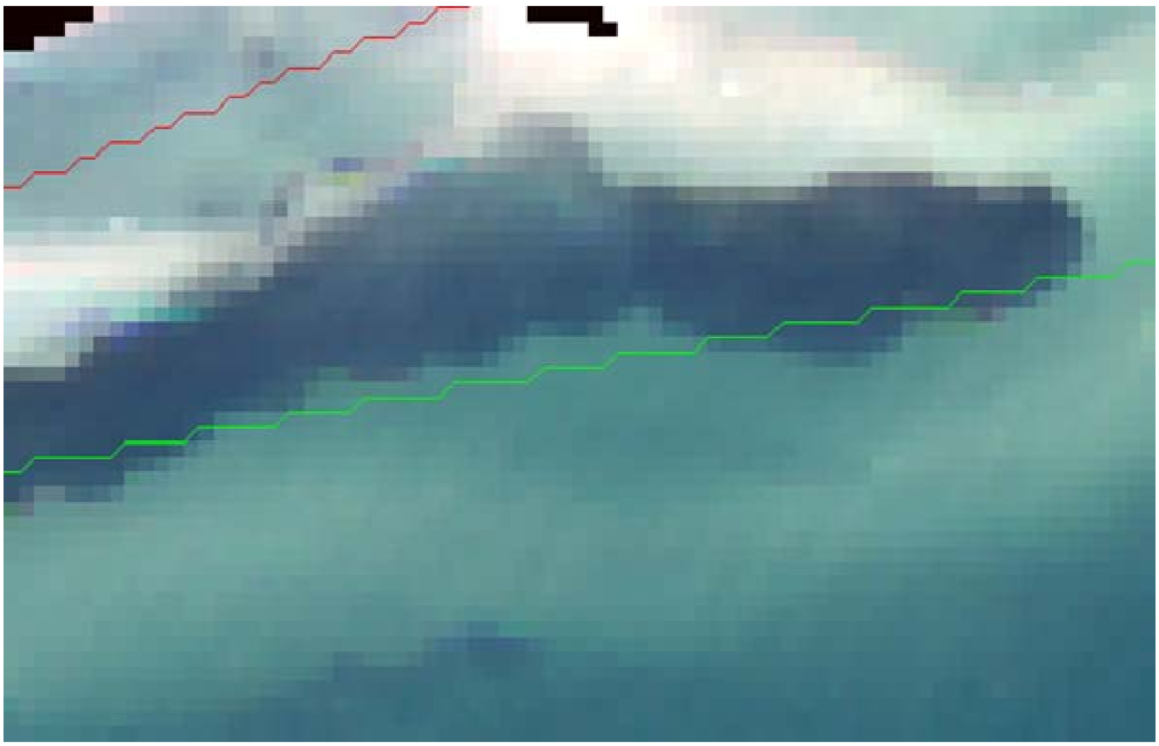


Figure 30. Transect 2 (green line) reef segment magnified.

Unlike Transect 1, the blue/green bathymetry profile is emergent over several of the sand bottom type segments. Only the blue/yellow bathymetry rises to a higher elevation than the blue/green ratio, reaching 2.06m (pixel 138). This occurs at a segment along the transect line that has the lightest sand. The reflectance plot (Figure 18) displays an increase in the yellow reflectance above that of the blue reflectance. At a meter depth or less, there is not enough water to attenuate the increased reflectance from the sand and the resulting calculation produced the above sea level heights.

The similar reflectance levels of the blue and yellow bands at this sand segment increase the emergent error, comparable to segments in which the blue and green bands have similar reflectance levels, driving that ratio's profile deeper. These lower reflectance values over the reef are analogous to reflectance values found at deeper water column depths. The blue/green derived bathymetry reports an erroneous depth, as if the calculation was result of expected water column attenuation and not bottom type.

The blue/yellow derived bathymetry displays a depth profile similar to the blue/green (Figure 29). The yellow band seems to assist the blue band over the dark reef segments as the blue/yellow bathymetry does not drop as deep as the blue/green, reaching only 4.0m as its deepest point over the reef bottom type. It seems the blue band has more influence in this ratio as the blue/yellow profile is closer in results to the blue/green than the other yellow or red ratios. Both ratio profiles have emergent elevations over the sand segments, resulting from the increase in reflectance of both bands.

The yellow/red bathymetry profile is the deepest profile for most of Transect 2. Like Transect 1, the yellow/red does not have such large depth changes over the varying bottom types but still displays the influence of the different albedos. The large difference between the DEM and the yellow/red bathymetry (Figure 31) is fairly consistent. The blue/green ratio mirrors the yellow/red in distance from the DEM when over the sand segment after pixel 100. Again, this is probably caused by the close reflectance levels involved in the bathymetry calculation. The other ratio combinations are above and below the DEM until the last segment of Transect 3 where the difference of all the ratios from the DEM is small.

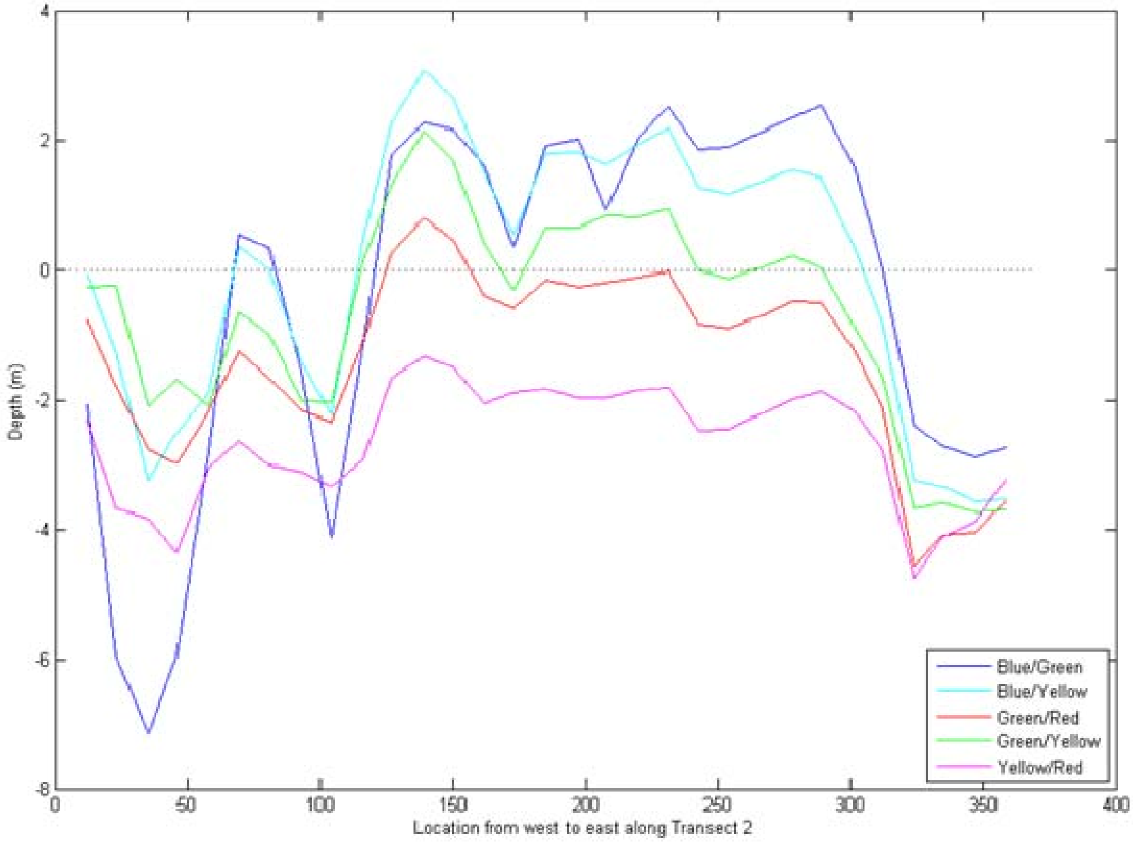


Figure 31. The difference between the derived ratios and the DEM along Transect 2. The difference was only taken at the corresponding DEM and ratio points from the smoothed data. There are 32 DEM points for Transect 2. The depth difference is the y-axis and the pixel location from west to east is the x-axis.

The last bottom type segment of Transect 2 is the blue water segment of sand (pixels 300:370). Here all the ratios have a steeper drop in depth than the DEM, though the DEM does begin to descend. Their depth profiles converge to a similar value (Figure 32). It is in this segment where no bottom type affects seem to be present, i.e., increases in the profiles due to the higher albedo of sand. This segment seems to be the result of water column attenuation where blue and green bands would be expected to be closer to the ground truth as the increased attenuation of the longer wavelengths results in deeper depths for those ratios with red or yellow bands.

This same significant drop in depth is observed in the Transect 3 when that line crosses into the blue water segment. Since the DEM is several years older than the WV-2 data, there is the possibility that the sand bottom of Tampa Bay has changed and does have a steeper drop in this area, where all the ratio profiles seem to agree in both Transect 2 and Transect 3. In the shallower depths of the DEM where the ratio bathymetry profiles are on either side of the DEM, there is less likelihood that the ground truth is significantly different in shape and slope from what is portrayed.

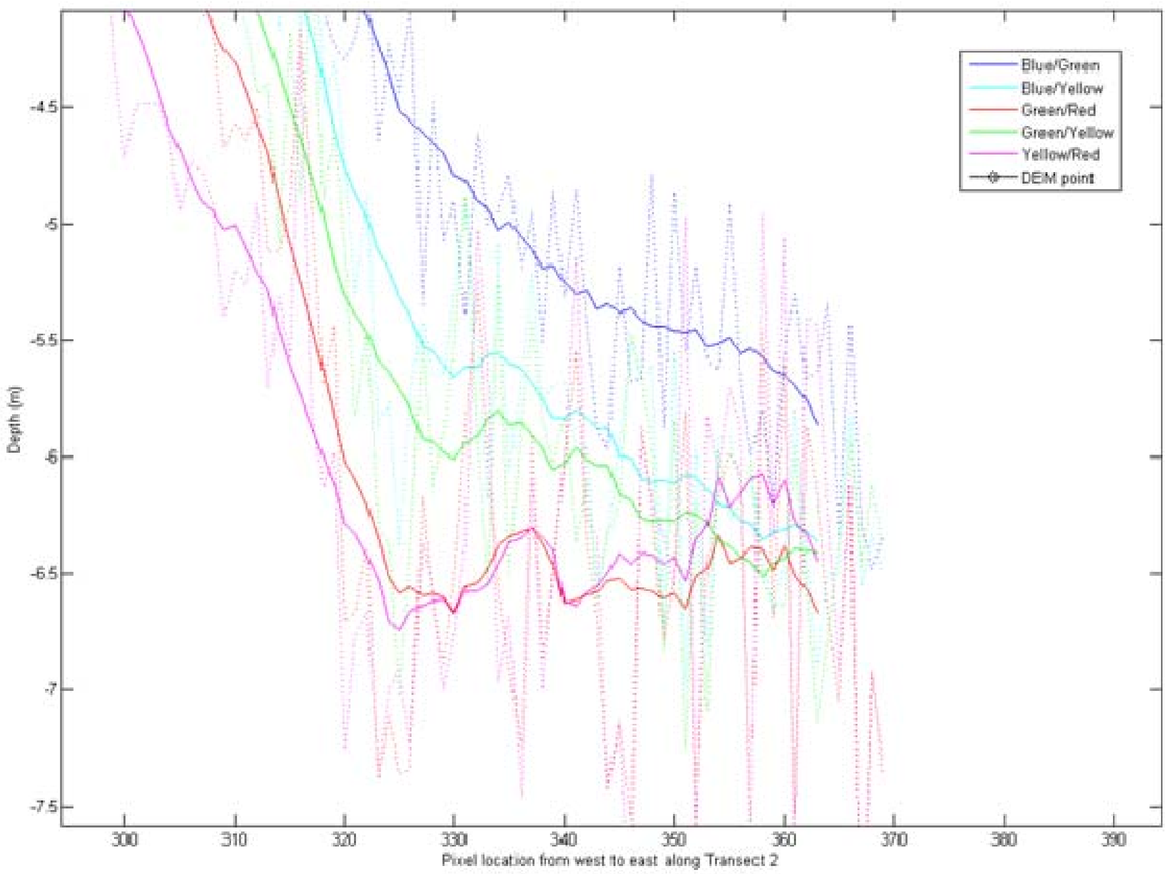


Figure 32. Magnification of the tail end of Transect 2 where all five ratios converge to a similar depth profile. The ratios using the longer wavelengths have a deeper profile than the shorter wavelengths but all display a profile based on water column attenuation.

3. Transect 3 Derived Bathymetry Comparison

Transect 3 is a perpendicular transect line from the coast to off shore that experiences the most depth change of the three transect line studied. The DEM profile

starts in the shallow reef area and proceeds south along a sand wave area until reaching the deep water, where the bottom is no longer visible. The DEM displays a sloping descent from the shallower reef segment (under a meter) to the deeper area of over 7 meters.

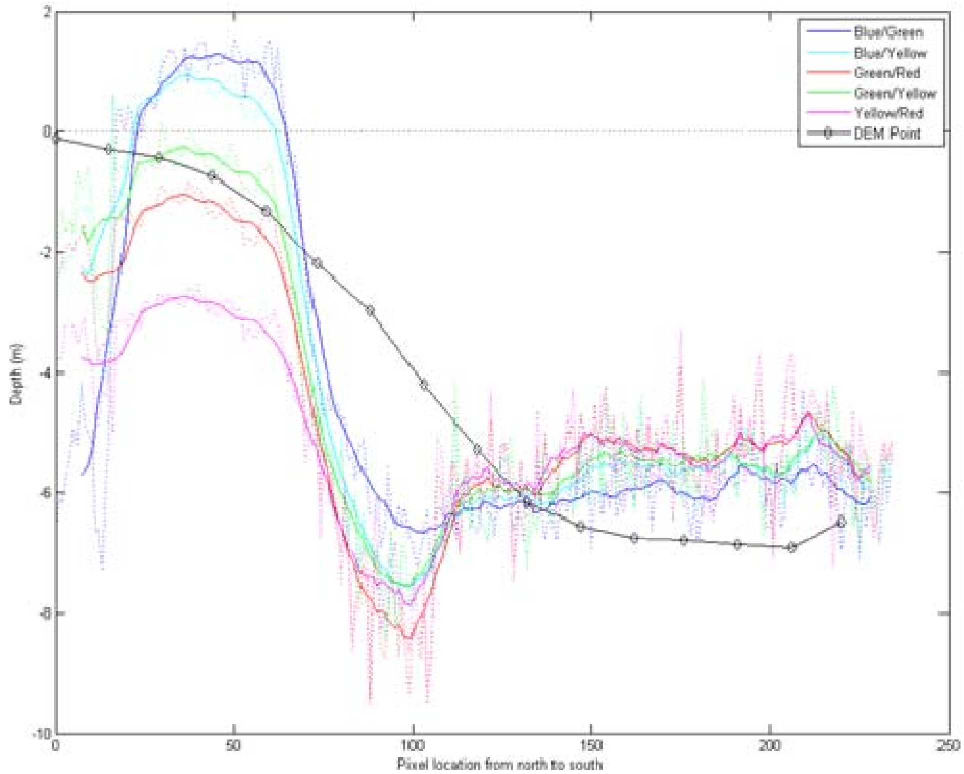


Figure 33. Transect 3 absolute bathymetry compared to the DEM. The solid lines are the running mean of each data set. The blue/green ratio is blue, the blue/yellow is light blue, the green/yellow is green, the green/red is red and the yellow/red is magenta. Depth is the y-axis and the pixel location is the x-axis.

The bathymetry profiles of the five ratio combinations on Transect 3 are very similar to each other (Figure 33). Like the transect lines compared above, the bottom type plays a part in the derived bathymetry calculations. Over the shallow but dark reef segment of Transect 3 there a noticeable difference between the DEM depth and the deeper ratio depths. This is expected in the low albedo environment of the reef segment that affected Transects 1 and 2 the same way. Again, the blue/green ratio reports the

deepest depth over there reef, 5.7m and the green/yellow, green/red and blue/yellow ratios handle the reef influences better within a couple meters of the DEM (Figure 34).

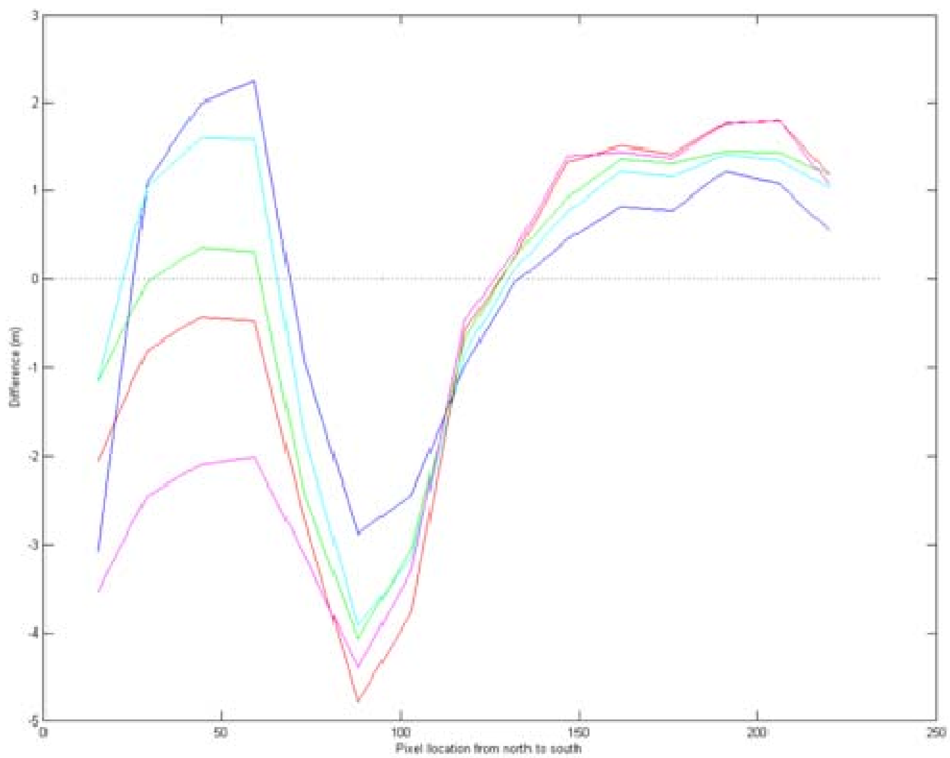


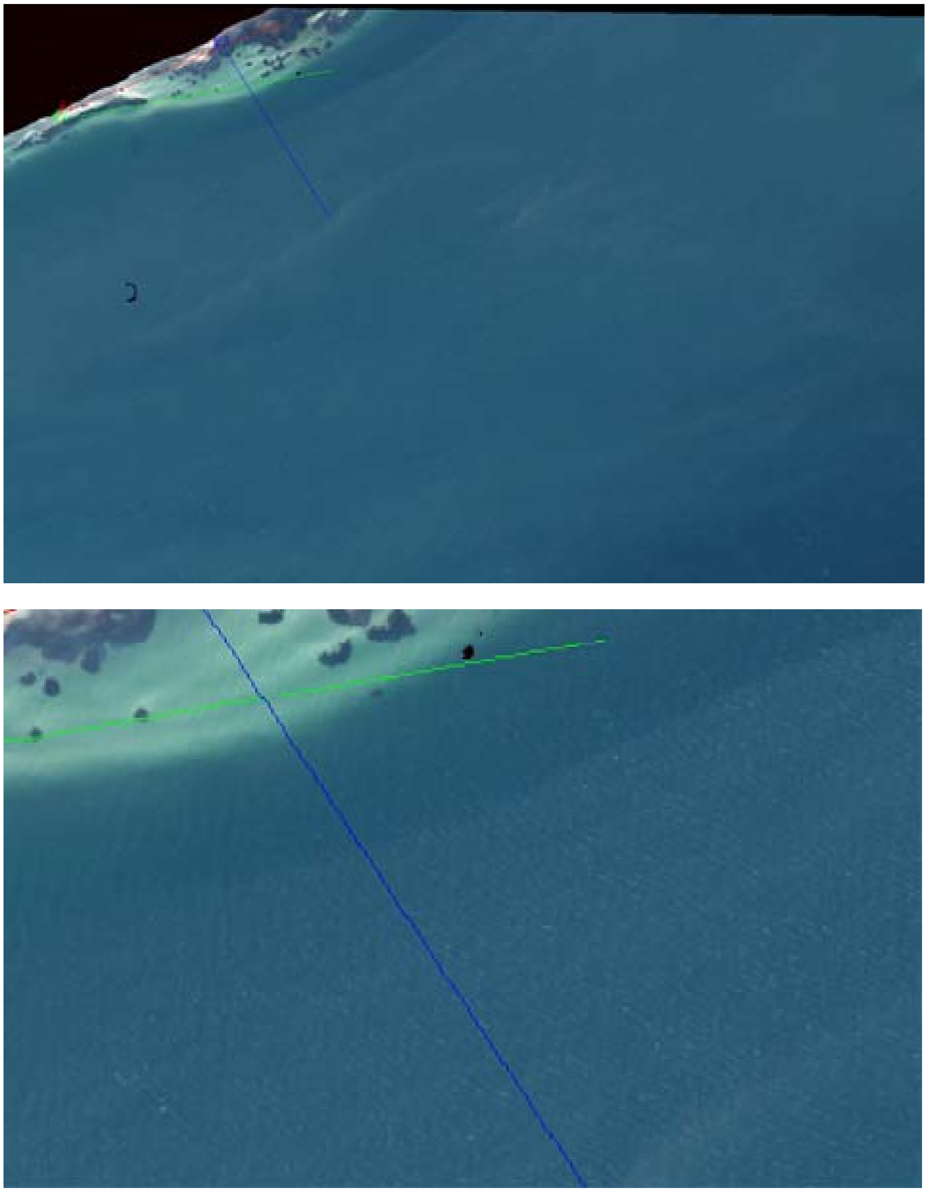
Figure 34. The difference between the derived ratios and the DEM along Transect 3. The difference was only taken at the corresponding DEM and ratio points from the smoothed data. There are 32 DEM points for Transect 3. The depth difference is the y-axis and the pixel location from west to east is the x-axis.

The sand bottom type spreads out the derived bathymetry as the difference in reflectance levels becomes apparent. The blue/green and blue/yellow ratios are emergent as they were in Transect 2. The green/red and green/yellow bathymetry is closest to the DEM for this sand segment.

The blue water segment has no noticeable influences for the supposed sand bottom type. The attenuation by the water column works to minimize any effects of the bottom and the result is more similar derived bathymetry profiles that follow the DEM closely for the last half of Transect 3.

The decrease of all ratios at this point on Transect 3 is the same as that observed at the end of Transect 2. All five ratio combinations suggest a steeper slope than the DEM, before rising back up to depth of the DEM. This could be caused by a change in the ground truth between DEM creation and WV-2 data collection.

The last portion of Transect 3, after the drop to deeper depths in the blue segment, experiences a change in the water column due to increased turbidity (Figure 35). The red and yellow reflectance levels increased (Figure 19b) and the ratio bathymetry with red or yellow bands, as a result are shallower than expected for this depth. The yellow/red and green/red ratio profiles are overlapping for most of this segment. The blue/green bathymetry is the closest to the DEM in this deep portion being about a meter different (Figure 34). The green/yellow and blue/yellow ratios are the next closest profiles to the DEM. The green/red and yellow/red ratios are the furthest away from the DEM, indicating that the red band was impacted the most by the change in turbidity.



(a)

(b)

Figure 35. The turbidity difference on Transect 3 is distinguishable in these RGB reflectance composites. The top is an overview of the transect area (a) and the bottom (b) is a close up of Transect 3 (blue) and Transect 2 (green) in either the blue water for both transects or more turbid water for Transect 3.

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V. CONCLUSIONS

A. BOTTOM TYPE EFFECTS: CASE STUDY 1

In case study 1 where the effects of the varying bottom type of Transect 1 are studied, the water column attenuation did provide a corresponding decrease in reflectance as the depth increased (Figure 20) over a dark reef with a low albedo. The color of the reef does play a role in the relative ratio results as noticed in the last two relative ratio/DEM comparison points in Transect 1. The increased red and yellow reflectance provided by the color of the reef provided enough augmentation in the reflectance of each band to produce shallower relative bathymetry, as if the transect line was over a shallower area. In shallow water, less than a meter, the near shore bottom type can contribute and even dominate the water column attenuation, thus producing error in the calculated bathymetry that is depending on the water column to have enough depth to mitigate the bottom type albedo.

Though Stumpf et al. (2003) is correct that the bottom type albedo does affect all the wavelengths, in very shallow depths, the water column attenuation cannot uniformly correct for bottom type effects. In low albedo bottom type environments, reflectance is reduced and in high albedo bottom type environments reflectance is increased. The increase and decrease of reflectance is not uniform as the color of the bottom type affects the amount of reflectance for each band. As in the case of the reef segment in Transect 1, the low albedo and water column attenuation worked together to proved a corresponding trend between the relative ratio and the ground truth. However, as the reef bottom type became more reddish brown, the increased reflectance overrode the attenuation and decreased the correlation between relative ratio and ground truth.

B SENSITIVITY TO SAND PATTERNS: CASE STUDY 2

The sand segment of Transect 3, where the reflectance data suggested a wave like pattern in the sand, which translated into a possible wave like pattern in the derived bathymetry. It takes careful observation of the pixels of the derived bathymetry profiles to find corresponding depth changes to the sand waves. The yellow band combinations

with blue and green bands provided a better visual image of the sand waves. The yellow/red, the blue/green and green/red ratios had a less obvious sand pattern (Figure 26).

The derivation of bathymetry is sensitive enough to find changes in the sand topology, such as the bottom sand waves produced by wave action. This is a function of the high resolution of the WV-2 data. There is still significant noise in the data that is difficult to distinguish by the depth profile without the color composite for comparison and location of the sand waves. Exploring changing sand patterns in satellite data would benefit the research field of change detection of the ocean bottom.

C. YELLOW SPECTRAL BAND CONTRIBUTION: CASE STUDY 3

1. Conclusions From Transect 1

The yellow band does not appear to produce a derived bathymetry that is as close to the provided ground truth as other ratio combinations in Transect 1. The yellow band appears to be more sensitive to the light sand segments and higher bottom albedo. This increased water leaving reflectance in conjunction with a very shallow environment produced above sea level results in the blue/yellow and green/yellow ratios. This is the result of the reflectance values having a small variations and overlapping at times along the transect line. The yellow band reflectance (Figure 16) did have higher reflectance than the blue or red bands over several sand segments. The yellow band does perform better in the deeper transects when over sand.

However, the yellow band combinations are less sensitive to the dark reef bottom type when compared to the other ratios. The blue/green ratio is very affected by the dark reef bottom type causing increased depth estimates. This is demonstrated in all three transects.

The green/red ratio produced a profile close to the DEM over the sand, which also occurred in the other two transects. The shade of sand could increase the red band’s reflectance enough to balance the green’s higher reflectance value. The difference of the red and green bands’ reflectance could be another factor that caused the green/red bathymetry to be near the ground truth.

2. Conclusions From Transect 2

Transect 2 demonstrates the sensitivity of derived bathymetry to bottom type and albedo at shallow depths similar to Transect 1. Instead of attenuation through the water column being the dominate term, the contribution by the bottom overrode the attenuation effects until the transect line reached greater depths. This is demonstrated by all the ratios behaving similarly over the sand segments. The five ratios all had comparably shallower profiles, caused by the increased reflectance from the high albedo of the sand. Conversely, the ratios result in a greater depth when they are over a dark reef segment. In the deep blue segment, where the bottom type is assumed to be sand but is not visible, there is no corresponding elevation of depth as in the other sand segments. Here the water column attenuation is a major contributor to the ratio bathymetry.

Using band combinations that are more separated on the electromagnetic spectrum seem to have less over all error along Transect 2. The outliers were blue/green and yellow/red ratios but other three ratios, blue/yellow, green/yellow and green/red, that have more difference between the center wavelengths, provided a more accurate representation of the ground truth. The longer wavelengths (yellow and red) that are more sensitive to water depth assist to balance out the shorter wavelengths (blue and green) that are not as affected by attenuation at these shallow depths.

Having the right albedo can assist in producing results close to the ground truth, as evidenced by the blue/green bathymetry being very close to the DEM when the sand was a dark shade. Otherwise, the sand was too high a reflectance for the blue/green or blue/yellow ratios to produce bathymetry close to the DEM. Albedo is a characteristic of the bottom type and cannot be changed. Instead, the albedo affects must be mitigated. The shade of the sand can increase or decrease the amount of reflectance observed and the ratio profiles are a reflection of the relationship of the different reflectance.

3. Conclusions From Transect 3

Though the Stumpf et al. (2003) method assumes minimal contribution for derived depth from the bottom type and its corresponding albedo, it is apparent in other works (Densham, 2005; Clark, 2005; Camacho, 2005) and this study, that albedo is still important. In shallow depths of Tampa Bay (no deeper than 2 meters) the contrasting colors of the reef and sand with their varying amounts of reflectance have a negative impact on the calculated bathymetry. High albedo substrates produced shallower depths and sometimes emergent depths due to the large increase in reflectance and low attenuation factor. Low albedo substrates work to produce deeper depths with less reflectance than expected.

Transect 3 is an excellent example of how Stumpf et al. (2003) equation works. The attenuation caused by the water column depth is reflected in all five ratio combinations in the deeper portions of this transect line. However, at depths less than 2 meters, the equation is also influenced by the bottom albedo characteristics. Both the sand and reef work to modify reflectance levels so that the derived bathymetry profiles are too shallow, emergent or too deep.

The yellow band's contributions are most evident in Transects 2 and 3, due to reducing the error difference in the calculated bathymetry compared to the DEM. The difference was caused by either the blue or the green reflectance variation over the changing bottom types such as the dark reef and sand. This is observed with the blue/yellow and green/yellow bathymetry demonstrating less error over the sand segment than the blue/green values. The sand does not contribute as much to the yellow reflectance as it did to the blue and green (Figure 19b). The green/yellow and green/red demonstrated the most accurate derived bathymetry over the sand when compared to the DEM.

When regarding the depth profile of Transects 3, it seems that the outliers are the blue/green and yellow/red ratios. The blue/green ratio is the furthest ratio above the DEM and the yellow/red ratio, the furthest below. Both the blue/green and yellow/red ratios are combinations of wavelengths with similar reflectance. Utilizing ratios with a

greater wavelength difference is beneficial, as demonstrated by the blue/yellow, the green/yellow and the green/red results nearer to the ground truth.

Though both the yellow and red bands assist to reduce the larger blue and green reflectance values, it is apparent that the red band's reduction of reflectance may be too large, since the green/red and yellow/red ratios where deepest over the sand segment of Transect 3. This suggests that utilizing all five bands can counteract the contributions of the bottom substrate and allow for tuning of the derived bathymetry.

D. FURTHER STUDY

There are many avenues of the further study for remotely sensed derived bathymetry. The use of the coastal blue band from WV-2 should be included in the combinations of ratios. In all of the transect lines studied, the ratio bathymetry profiles were either more shallow or deeper than the ground truth. An investigation into a weighted average that could assist in the mitigation of the bottom type influence should be investigated for the use of derived multi-spectral bathymetry products.

Another research area would be to conduct derived bathymetry studies with ground truth of similar resolution and nearly concurrent time of collection. This would increase the accuracy of the remotely sensed products.

One of the most useful applications of satellite data is change detection research, which takes advantage of the quick revisit time satellites have. The high resolution of the WV-2 satellite and future satellites, along with the incorporation of multi-spectral bands demonstrate continuing applicability of remote sensing for bathymetry applications and other military uses.

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APPENDIX. LINEAR REGRESSIONS

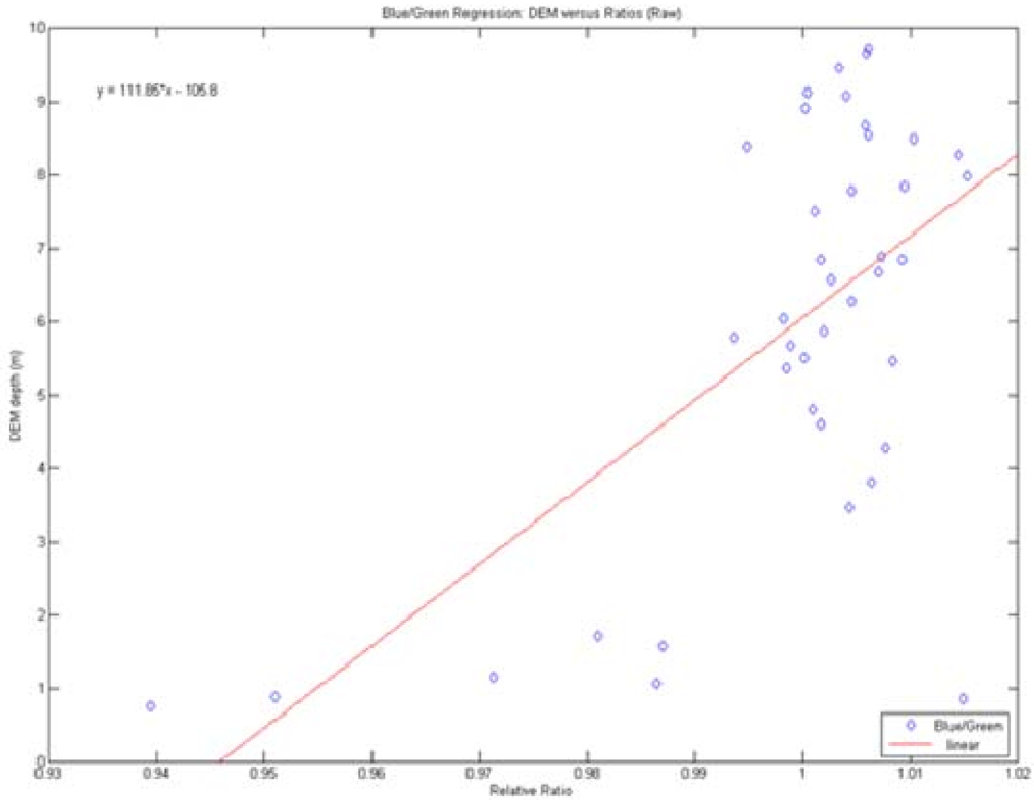

Figure 36. Linear Regression for the Blue/Green ratio using 40 points. The x-axis is the ratio value and the y-axis is the corresponding DEM value at that pixel. The MATLAB Curve Fit tool was used to create the regression.

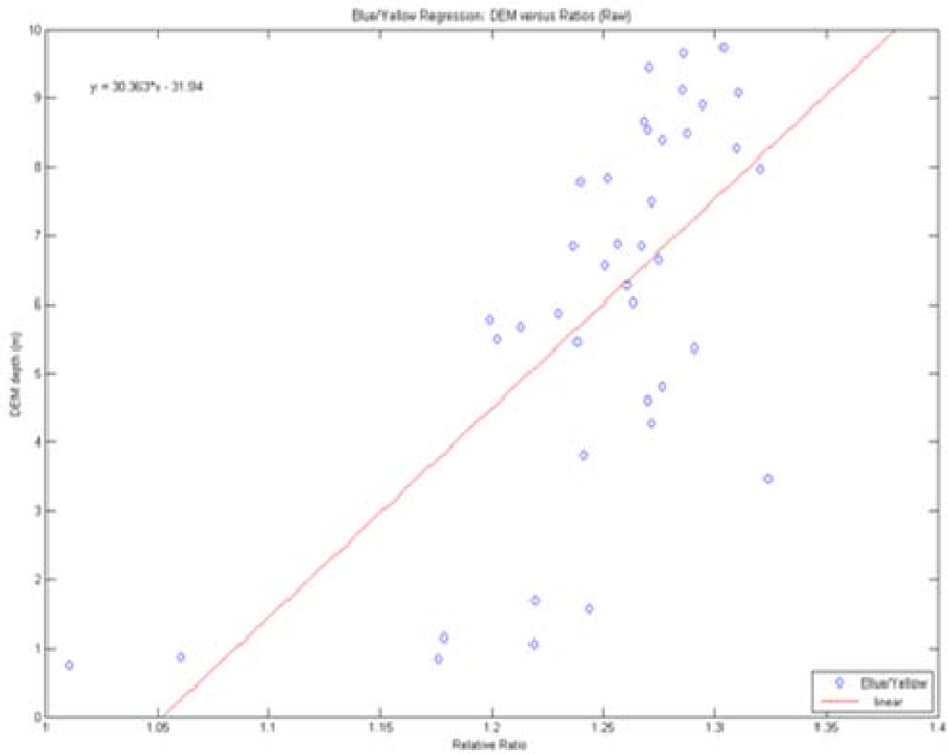

Figure 37. Linear Regression for the Blue/Yellow ratio using 40 points. The x-axis is the ratio value and the y-axis is the corresponding DEM value at that pixel.

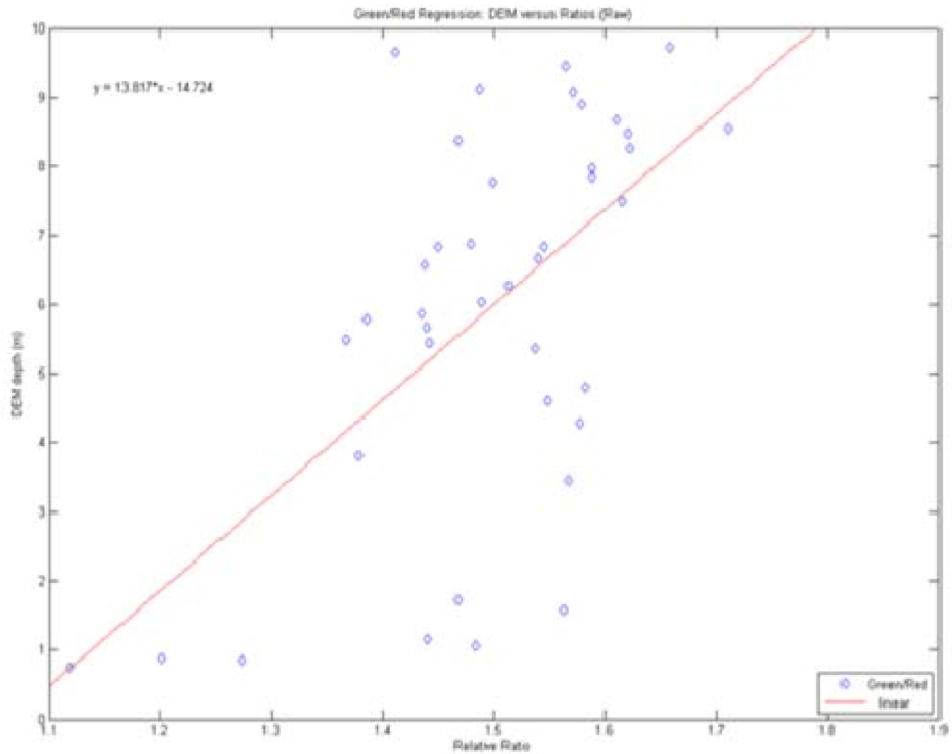

Figure 38. Linear Regression for the Green/Red ratio using 40 points. The x-axis is the ratio value and the y-axis is the corresponding DEM value at that pixel.

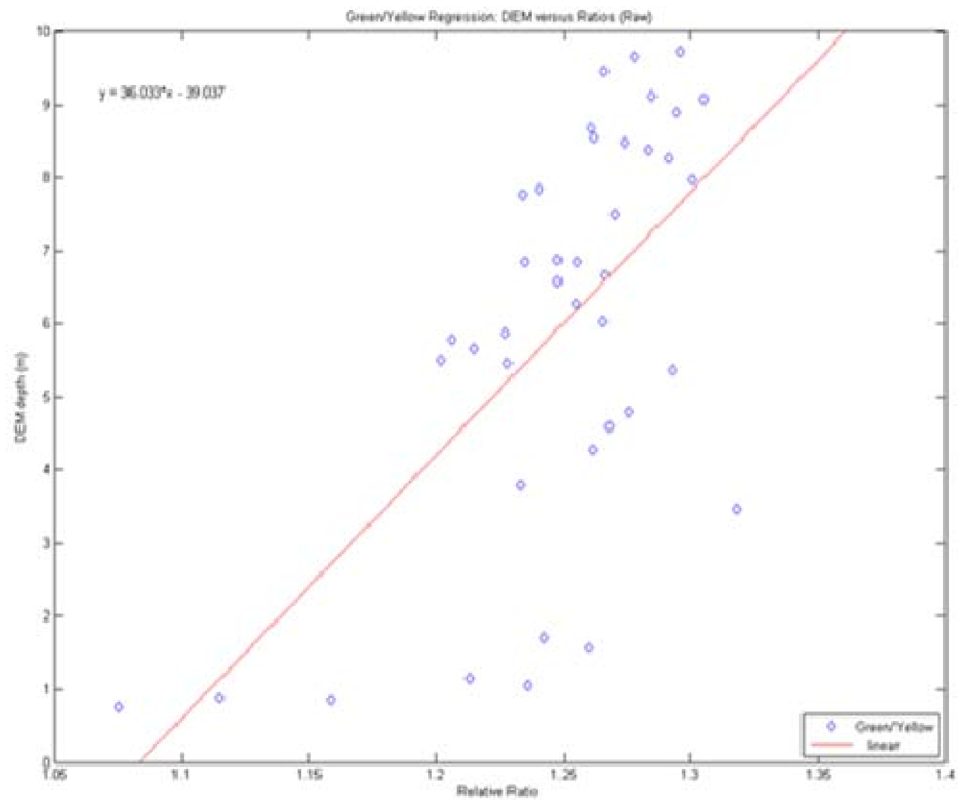

Figure 39. Linear Regression for the Green/Yellow ratio using 40 points. The x-axis is the ratio value and the y-axis is the corresponding DEM value at that pixel.

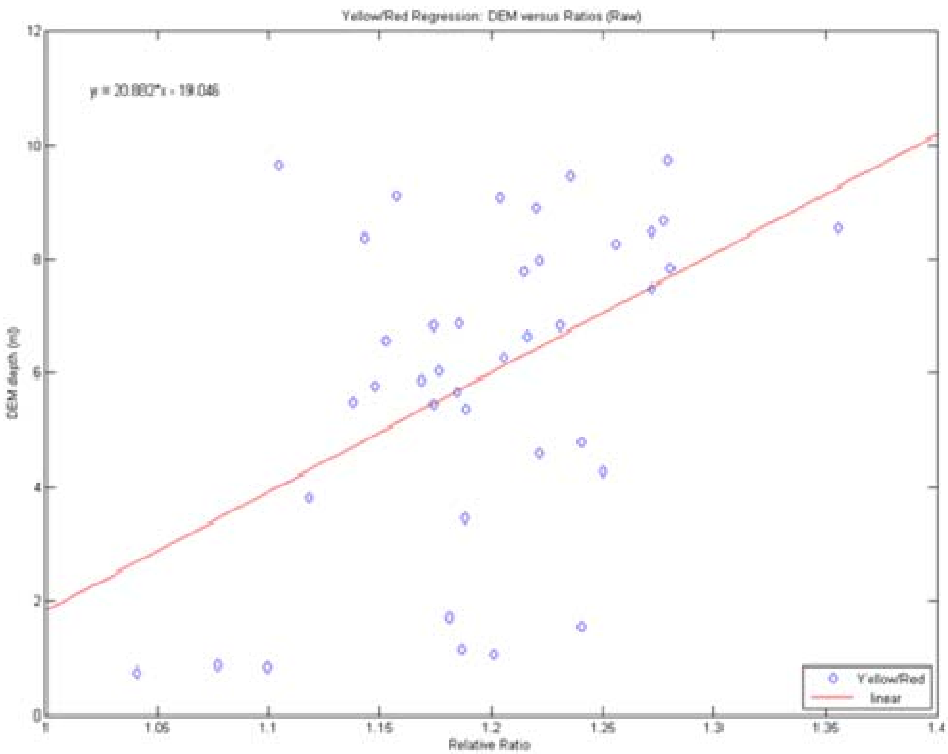

Figure 40. Linear Regression for the Yellow/Red ratio using 40 points. The x-axis is the ratio value and the y-axis is the corresponding DEM value at that pixel.

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